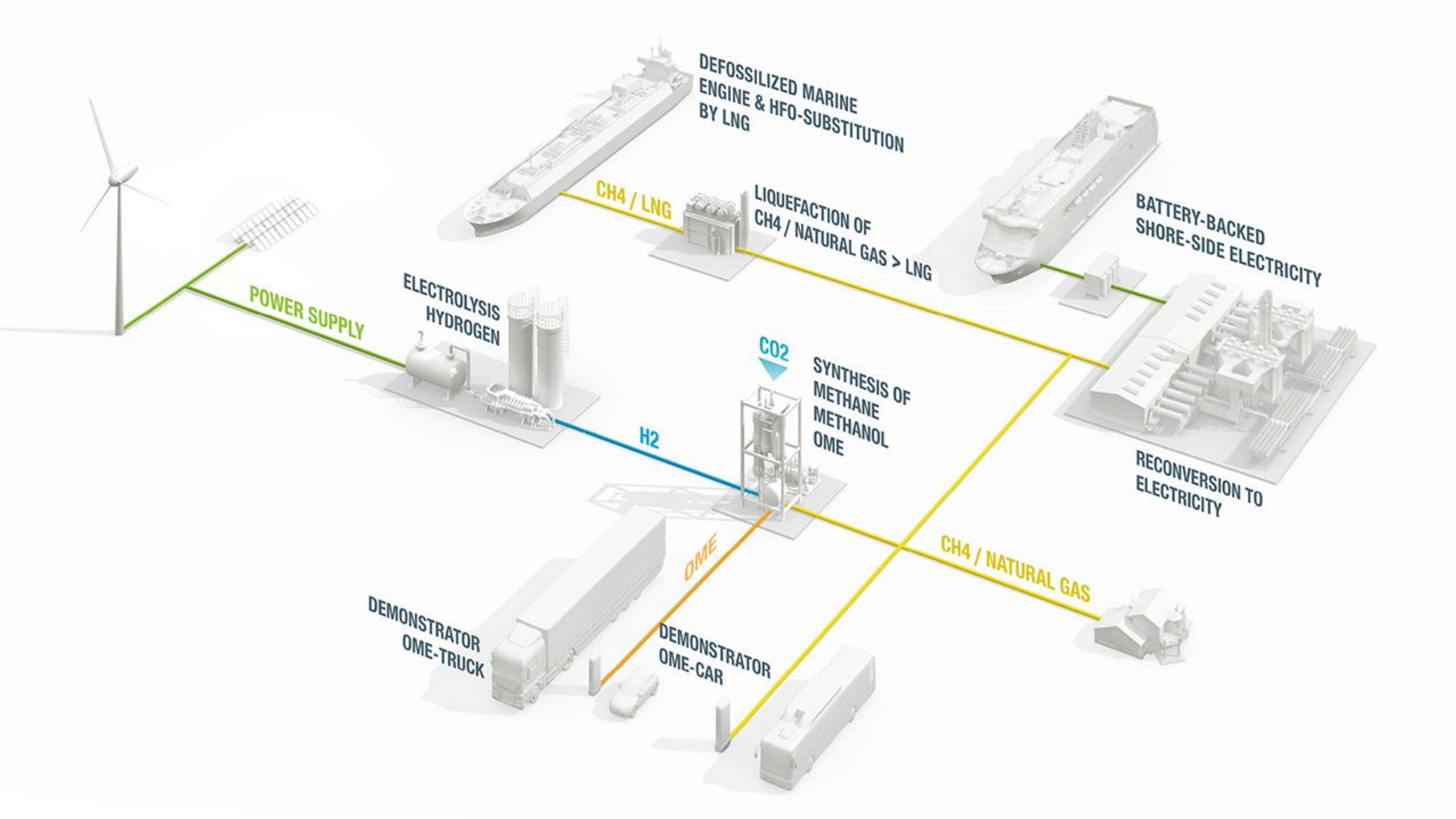

AALBORG UNIVERSITET
STUDENT REPORT

THE TECHNO-ECONOMIC VIABILITY OF POWER-TO-X TECHNOLOGIES

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AALBORG UNIVERSITET
STUDENT REPORT

Title:

The techno-economic viability of Power-To-X technologies

Theme:

An assessment of the techno economic viability of a PtX plant and the GHG emission reductions by a PtX plant.

Project Period [DD-MM-YYYY]:

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Sustainable Energy Planning and Management

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Abstract:

This study investigates the research question: *"To what extent is Power-To-X technologies techno-economically[1] viable in conjunction with the off-shore wind farms planned for the North Sea by 2030 and which benefits could the Power-To-X technologies offer to the efforts of reducing GHG-emissions?"*. To investigate this an abductive research approach was utilized, as the study creates a hypothesis, which will be used in combination with some objective values to infer the techno-economic viability and the GHG emission reductions of a suggested PtX plant. Furthermore, to infer the possible approach to make the suggested PtX plant more techno-economically viable. The hypothesis will be created through two theories, path-dependency, and institutional change. The objective knowledge will be created through multiple scenarios which will be modelled and tested in different constraints.

1 CONTENTS

2 PREFACE

This study is made by a student which attends Aalborg University, on the fourth semester of the Master program: Sustainable Energy Planning and Management. This study is a master's thesis, which investigates the techno-economic viability and GHG emission reductions of a Power-To-X plant, a subject which is within the master programs area of expertise.

I would like to thank Anders N. Andersen for sharing his knowledge and insight during our consultations, as well as for being outspoken, when providing feedback to the study. Furthermore, I would like to thank Anders N. Andersen for providing his time to give feedback and providing extra insight.

It is recommended that this report is printed in color and is read chronologically. Printing in color will enable the reader to easily distinguish between the different results in the analysis.

There are two addendums in this study, one is included in the report, the other is attached as a excel file, which contains all the data which will be used as inputs in the model, all the calculations and all the model outputs. These are:

- Appendix A – Mail Correspondance
- Appendix B – Energy System Data

3 NOMENCLATURE LIST

3.1 SPECIAL SYMBOLS

C : Capacity

[DKK] : Danish krone

E : Energy

I : Income

i : interest rate

[kJ] : Kilojoule

[kWh] : Kilowatt-hour

m : Mass

[m] : Meter

M : Molecular weight

[MPa] : Megapascal

[MW] : Megawatt

[MWh] : Megawatt-hour

n : Amount of substance

t : time period

T : Timeseries

x : Number

η : Efficiency

ΔH : Calorific value

3.2 ACRONYMS

AR: Annual Repayment

CFSR2: Climate Forecast System Reanalysis version 2

CHP: Combined Heat and Power

DAC: Direct Air Capture

DEA: Danish Energy Agency

DRPP: Down Regulation Power Price

DRPV: Down Regulation Power Volume

EV: Electric Vehicle

GHG: Greenhouse Gas

ICE: Internal Combustion Engine

ICEV: Internal Combustion Engine Vehicle

NP: Net Payment

NPV: Net Present Value

PCC: Post-Combustion Capture

PtX: Power-to-X: The X denotes a given fuel.

SOEC: Solid Oxide Electrolyzer Cell

SDRPP: Special Down Regulation Power Price

SDRPV: Special Down Regulation Power Volume

TIC: Techno-institutional complex

TSO: Transmission System Operator

4 INTRODUCTION

In this study, it has been found that Denmark has some ambitious goals regarding the reduction of greenhouse gasses (GHG), of the different sectors in Denmark. In this study it has been construed, that the different sectors which emit GHGs, will be partially electrified. But it has also been construed that some of these different sectors will have trouble with transitioning to electricity, which means that they need some other fuel, which has to replace the use of fossil fuels. In this study, it has been found, that electrofuels might be a great substitution, as it is produced through electricity. In this regard, it has been found that the Danish government want to build a wind farm in the North Sea and a Power-To-X (PtX) plant in conjunction with the wind farm.

As Denmark also wants to influence the rest of the world, it has in this study been assumed that Denmark will be a pathfinder, which will begin to commercialize the use of electrofuels. This might make it possible for the rest of the world to adopt the technology. But it has been speculated that the rest of the world, might only adopt the use of electrofuels, if the technology is economically viable.

In this regard, the study intends to investigate the techno-economic viability of the Power-To-X (PtX) plant, which will be established in conjunction with the wind farm. Furthermore, the GHG emission reductions caused by this PtX plant will also be investigated, as the emission reduction is the cause for the PtX plants establishment.

This study will be conducted through an abductive research approach, where hypotheses and objective knowledge, will be used in combination with each other. These will be used to establish what the techno-economic viability and the GHG emission reduction of the PtX plant might be.

The hypothesis will be established through two theories, the first called path dependency and the second called institutional change. The theory of path dependency will describe how the past development shapes the conditions for the development of the future. Through path dependency it is theorized that a carbon emission lock-in has occurred. Furthermore, the theory states that the lock-in will be hard to escape due to a techno-institutional complex. The theory of institutional change, describes how one theoretically can escape a lock-in, such as the carbon emission lock-in.

The objective knowledge will be established through multiple scenarios, consisting of different PtX plants with different operational approaches, which will be modelled in EnergyPRO. These scenarios will be established through literature studies and assumptions, as well as through calculations. The sensitivity of each of these scenarios will also be assessed.

Two main outputs of the model will be the annual operational revenue and the annual methanol production. The first output will be used together with the financial parameters of the scenarios, in order to establish the techno-economic viability and the second output will be used to establish the GHG emission reduction. This will be done for all the scenarios. The scenarios results will be evaluated through a multicriteria evaluation, which will enable the study to find the optimal scenario based on the different criteria.

The optimal scenario will then be compared Denmark's goal, and the theory of institutional change will then be used together with the objective results, in order to establish a proper institutional change approach. This culminates in a suggestion to an approach, which might enable Denmark to establish a PtX industry.

5 Problem analysis

In this chapter the problem, which will be investigated in this study, will be discovered. This problem will be found by assessing some of the mayor problems which Denmark is facing. Then these problems and the approaches used to solve them, will be assessed in order to funnel the problems down to one specific problem, which seems necessary to investigate.

5.1 The Danish CO_2eq emission reduction goal

In 1987 the Brundtland report was published, this report enlightened people about the different ways which humans pollute the earth and how the pollution might impact the future generations. A part of this report described the threat of climate change, which can be caused by the utilization of fossil fuels. In 1990 Denmark acknowledged and acted upon the threat, which GHG emissions cause towards the climate, by establishing the first emission reduction goal for any country. In the following years after the first emission reduction goal, different policies were established, in the efforts to reduce GHG emissions. (Dansk Energi, 2020) In 2019 the current Danish government, led by Socialdemokratiet, passed a climate law in the Danish parliament, in cooperation with the Danish parties Radikale Venstre, Socialistisk Folkeparti, Enhedslisten, Alternativet, Venstre, Dansk Folkeparti and Det Konservative Folkeparti. This law stated that Denmark must take leadership in the transition to green technologies, as well as actively work towards the Paris agreement's goal, of keeping the global temperature rise below 1.5°C. (Folketinget, 2019)

The involved parties agreed that Denmark must strive to reduce its Greenhouse Gas (GHG) emissions with 70%, in comparison to the base year of 1990, by the year 2030. (Folketinget, 2019) As the GHG emissions in the base year of 1990 were 75.7 million tons of CO_2eq each year, the goal is therefore to reduce the GHG emissions to 22.71 million tons of CO_2eq each year. (Klimarådet, 2019) The GHG emission reductions caused by the different policies from 1990 till 2020, and the present goal to reduce GHG emissions by 2030, is illustrated on figure 1.

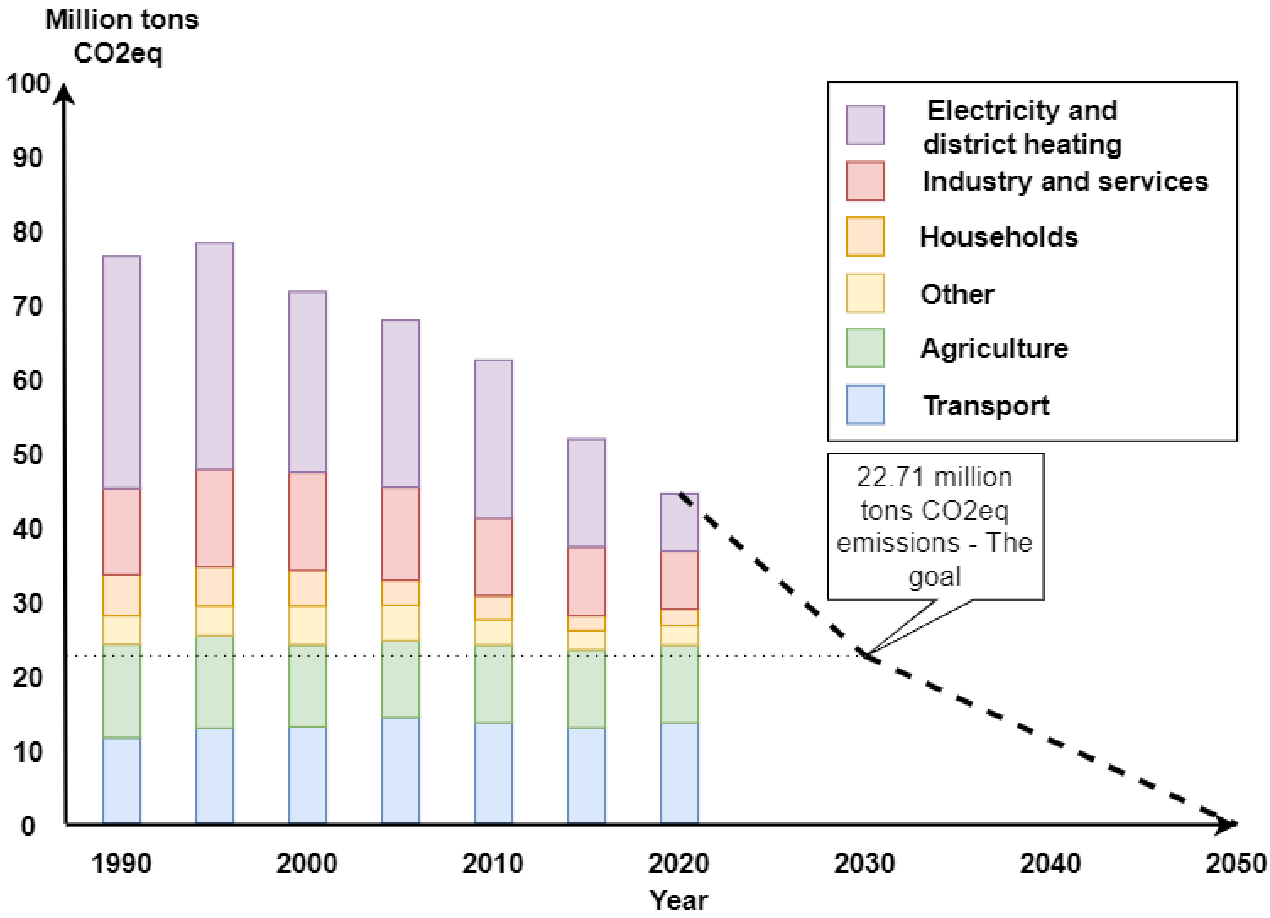

Figure 1 – Indicates the different CO_2eq emissions caused by each sector, from the base year of 1990 to 2020. The figure indicates the rate of GHG emission reductions, which must occur each year, between 2020 and 2030, in order for the goal to be met. Furthermore, the figure shows the buffer which the 70% emission reduction goal, will create for the last two decades before Denmark must reach emission neutrality. (Bloch, 2021)

As described in the purpose description of the Climate Law, the goal of the law is to ensure that Denmark keeps its status as a pioneering country within climate action. The law states that the intent of the goal is to inspire the rest of the world, by furthering the development of green technologies and thereby transitioning the Danish industry to green technologies, showing that Denmark can transition to green technologies while maintaining its competitiveness on the global market. The law states, that the government will support the development of green technologies and thereby the Danish industries transition towards green technologies, through public finances. Although, this transition must be as cost effective as possible. (Folketinget, 2019) Through the Climate Laws purpose description, it can be construed that the Danish government want to facilitate the development of new green technologies and the transition of the Danish industries towards green technologies. It can be construed that this is done in order to create a green industry which is located in Denmark and can be exported to the rest of the world, increasing the Danish welfare, while also causing a large decrease in the worlds GHG emissions.

5.2 THE CURRENT CO_2EQ EMISSION REDUCTION AND THE FUTURE APPROACH

The following section will describe the different GHG emission reductions in each sector, as well as the cause behind these emission reductions.

5.2.1 The electricity and district heating sector

As can be seen on figure 1, the GHG emissions from the electricity and district heating sector, has significantly decreased between the years 1990 to 2020. This GHG emission reduction has been obtained by many different means.

Firstly, the emission reductions stem from Denmark establishing a high production capacity of wind turbines, and a smaller capacity of photovoltaics. Secondly, the emission reduction stems from Denmark refitting their CHPs, so that instead of the CHPs utilizing coal, the CHPs utilize biomass which is considered a carbon emission neutral fuel. Thirdly, the emission reductions stem from the adaptation of electric boilers, heat pumps, solar collectors, and heat storages. (Energistyrelsen, 2020e)

In 1990 when the first GHG emission reduction goal was made, the wind turbine technology was not well developed, as the largest wind turbines capacity were 225kW, which meant that the former wind turbines did not have any commercial impact. The former Danish governments therefore supported the development of commercial wind turbine manufacturers, through different development packages. Furthermore, the different Danish governments have supported the power supply companies, which utilized the wind turbines, this was done through subsidies. These incentives for the wind turbines, is therefore the reason for why the current wind turbines were developed. Furthermore, these incentives are the reason for why the current wind turbine capacity is high in Denmark and is therefore one of the reasons for the GHG emission reductions of Denmark. (Energistyrelsen, 2009) Now the Danish wind turbine industry is self-reliant and created 142.6 billion DKK as off late 2019. (Wind Denmark, 2021) This means that through corporate taxes, the wind turbine industry is beginning to return the value which was invested in them.

The establishment of the current photovoltaic capacity happened within the last decade, where the photovoltaic power production capacity suddenly rose from 7MW in 2010 to 782MW in 2015 and to 1080MW in 2020. (Energistyrelsen, 2020e) This happened because the price for photovoltaics dropped to an affordable level, and together with the 60/40 subsidy scheme, the applications for subsidies increased dramatically and their approval led to the establishment of the photovoltaics. The 60/40 subsidy scheme states that the approved applicant may receive 0.6DKK for each kWh produced in the first 10 years of the photovoltaics lifetime, following the first subsidy’s expiration the photovoltaics would then receive 0.4DKK for each kWh produced in the next 10 years of the photovoltaics lifetime. The subsidy scheme was dropped, as there were applied for 4500MW capacity, which was 3500MW above the targeted capacity. (Ingeniøren, 2016a & Ingeniøren, 2016b)

The reason that the coal fired CHPs were refitted, to be able to use biomass as a fuel, was because the CHPs would be able to receive a subsidy of 0.15DKK for each kWh electricity produced through biomasses. (Energistyrelsen, 2021e) Furthermore, there are no taxes associated with the consumption of biomass, which together with the increase in coal prices, made the biomass cheaper to consume in order to produce electricity and heat. (Ingeniøren, 2008 & Ingeniøren, 2018)

Heatpumps and electric boilers are being used in combination with heat storages, as supply companies can utilize the cheap electricity to produce heat, which often occurs in conjunction with wind turbines producing large amounts of electricity. Furthermore, the heat storages are being used together with CHPs, in order to create a flexibility for the CHPs power production. (Bloch et al., 2019)

Through this assessment, it becomes apparent that a continuation of the development, will result in the electricity and district heating sector becoming CO_2eq emission neutral.

5.2.2 The industry and services

As can be seen on figure 1, the industry and service sector has decreased its emissions by decreasing oil, natural gas, coke, and coal consumption. Furthermore, the industry and service sector has increased its consumption of renewable energy. It is important to note, that this GHG emission reduction was not caused by a decline in Denmark's industry. Denmark's production of each unit of products has increased and the energy consumption for each unit of product produced has decreased. (Energistyrelsen, 2020e) It is expected that large parts of industry and services will be electrified, but there are other parts of the industry which cannot be electrified, as their production relies on the properties of fuels. The parts of the industry which cannot be electrified, can either be converted to be compatible with biomass, or they can utilize electrofuels which are considered to be GHG emission neutral. (EA, 2020)

As parts of the industry becomes electrified, their emissions become connected with the electricity sector, which means that if the electricity sector becomes carbon emission neutral so will the electrified industries. As biomass is already readily available, and electrofuels are not, electrofuels can be viewed as a key missing component to making the industry GHG emission neutral.

5.2.3 The Danish Households

Figure 1 indicates that the GHG emissions from the Danish households have diminished, from 1990 towards 2020. This emission reduction has been caused by a higher proportion of households insolating their houses, consequently lowering the energy consumption. Insolation is a requirement for newly built houses and sometimes a requirement for old houses which are being refurbished. (SparEnergi.dk, 2021) A part of the emission reduction from Danish households, can be attributed to a part of the households being connected to their local district heating grid, which means that their energy consumption is moved to the electricity and district heating sector and is therefore connected with the emissions from that sector. Furthermore, the Danish households which cannot be connected to the district heating grid, has either adopted heat pumps or biomass boilers. (Energistyrelsen, 2021g) This conversion has resulted in a decrease in oil consumption, consequently lowering the emissions from Danish households. (Energistyrelsen, 2020e)

As it is no longer permitted to get an oil or gas boiler, and the Danish households are expected to either be connected to the district heating grid or utilize heat pumps in the future, the GHG emissions from the households are going to disappear. (Energistyrelsen, 2021f & Energistyrelsen, 2021g) The energy consumption which is moved over to the electricity and district heating sector, is expected to be covered by green energy sources as explained in section 5.2.1, which means that both sectors can be expected to reach zero emissions with the existing approach.

5.2.4 The agriculture sector

As can be seen on figure 1, the agriculture sector has decreased its emissions between 1990 towards 2020, a reduction which is above 20%. The emissions from the agriculture sector are attributed to the CH_4 and N_2O emissions, which are associated with the animal's digestion and decay of plants and manure. Furthermore, the GHG emissions of the agriculture sector originates from loss of ammonia due to nitrogen leaching into the ground, as well as emissions due to land use change, such as deforestation and drainage of land. Lastly the GHG emissions from the agriculture sector, can be attributed to the use of fossil fuels in the production of crops. (Olesen, 2017)

The exact emissions of the agriculture sector are hard to quantify and are typically estimated through simplified calculation methods, with the exception of the agricultures fossil fuel consumption. The emissions of the agriculture sector are estimated to be about 9.6 million tons of CO_2eq in 2017. (Olesen, 2017) The emissions from the agriculture sector's fossil fuel consumption, was around 1 million tons of CO_2eq in 2020. (Energistyrelsen, 2021h)

The approach to reducing the GHG emissions from the agriculture sector, is presently heavily debated and many of the different proposals are being disputed. The Climate Partnership for the Food and Agriculture Sector has estimated that the emissions from the agriculture sector, can be reduced by 62% towards 2030, by utilizing different available technologies and production practices. Technologies and practices which reduces the emissions of N_2O and CH_4, as well as emissions from land use change. These technologies or production practices could be better stable systems, better feed, nitrification inhibitors, vertical farming, and pyrolysis technologies to produce bio coal from hay and manure. (Ingeniøren, 2021) Another emission reduction might be achieved by converting the energy consuming technologies in the agriculture sector to green technologies, similarly to the industry and service sector. 40% of the energy consumption is used for space heating and 60% is used for farming equipment to produce the crops. (Energistyrelsen, 2021h)

This means that if the agriculture sector is converted similarly to the industry and service sector, 40% of the emissions can be removed through electrification and 60% through electrofuels. As of now the agriculture sector's emissions cannot be completely removed, but with an emission reduction of ~72% the 2030 goal can be meet and there is a buffer towards 2050, where the remaining approaches can be found.

5.2.5 The transportation sector

As can be seen on figure 1, the GHG emissions from the transportation sector has increased between 1990 and 2020, this increase is calculated to be 30%. (Energistyrelsen, 2020e) The emissions from the transportation sector are mainly caused by the energy use of internal combustion engine vehicles (ICEV), where the remaining emissions are caused by vans, trucks, busses, domestic planes, railroads, domestic ships, and ferries. (Energistyrelsen, 2020e)

It is expected that some of ICEV fleet will be gradually replaced by electric vehicles (EV), towards the year 2030 and that the ICEV fleet will be fully replaced by EVs by the year 2050. (Asuamah et al., 2020) The rail roads are partially expected to be electrified towards 2030 and can be expected to be fully electrified towards 2050, due to Banedanmark's current plans. (Banedanmark, 2021) But the electrification of the whole transport sector is not possible, because trucks, ships and planes are not expected to have the same operational capability with electricity. Trucks, ships, and planes can be categorized as heavy-duty transportation, which needs fuels to operate properly. It is expected that the heavy-duty transportation could become emission neutral, if they utilized electrofuels as a fuel. (Mathiesen et al., 2015)

5.2.6 The energy island in the North Sea

In 2021 the Danish government, led by Socialdemokratiet, entered into an agreement with the Danish parties Radikale Venstre, Socialistisk Folkeparti, Enhedslisten, Alternativet, Venstre, Dansk Folkeparti, Det Konservative Folkeparti and Liberal Alliance. The agreement described the construction and ownership of an Energy Island, which is planned to be established in the North Sea. The energy island is planned to consist of different wind farms with a total capacity of 3GW in 2030, with a potential capacity increase of 10GW. (Regeringen, 2021) From section 5.2.1-5.2.5 it can be construed that these wind farms will be established, in order to ensure that when the different sectors begin to electrify their consumption, the electricity sector will be able to deliver green electricity in correspondence with an increased electricity demand. Furthermore, another intent of the energy island is to convert green electricity from the wind farms to electrofuels, which can be used in ships, planes, and trucks. (Regeringen, 2021) But through section 5.2.1 to 5.2.5, it can be stated that these electrofuels can also be used to decrease the GHG emissions from other sectors.

But even with political demand for electrofuels, which is intended to displace fossil fuels in order to decrease GHG emissions, it is unknown whether electrofuels make sense in a business perspective and can compete against fossil fuels. Because if the Danish government want to inspire the rest of the world's nations, to transition away from fossil fuels, it could be argued that they would only do so, the benefits of utilizing electrofuels outweighs the use of fossil fuels.

Research question

"To what extent is Power-To-X technologies techno-economically[1] viable in conjunction with the off-shore wind farms planned for the North Sea by 2030 and which benefits could the Power-To-X technologies offer to the efforts of reducing GHG-emissions?"

1. *What is the techno-economic value and GHG emission reduction of the Power-To-X technologies at different production capacities?*
2. *In regard to the techno-economic value and GHG emission reduction, what is the proper production capacity of Power-To-X technologies, in comparison to the wind farms planned for the North Sea by 2030?*
3. *Which efforts could be made to enhance the techno-economically viability of the Power-To-X technologies?*

Delimitation

1. This study will not assess the societal costs associated with the Power-To-X technologies.
2. This study will work with 2030-year goal in mind, even though some argue that the wind farms in the North Sea and the Power-To-X technologies will not be established before 2033, because the Danish industries are pushing for their earlier establishment.

[1] Techno-economic implies a given technology's operational performance to accomplish its task, together with the whole operational expenditure and revenue associated with the technology accomplishing the task. Techno-economically viable therefore implies the technology's ability to perform a task, when the technology is constrained by different parameters, and be profitable when taking the investment cost, operational revenue, operational and maintenance cost into account.

6 RESEARCH DESIGN

This study will be conducted through an abductive research approach. An abductive research approach is when a hypothesis together with observed facts are inferring a phenomenon. This means that this study will hypothesize the techno-economic viability of a PtX plant, as well as hypothesize the PtX plant's influence on the climate, based upon the past experiences. Then this study will develop an investigation of what the techno-economic viability and emission reduction of a PtX plant might be. Then the hypothesis will be used together with the investigation, to describe the possible development of the PtX plant. It is important to note, that the hypothesis and investigation will not be used to prove or construct each other but will be used in a combination with each other to imply a possible future development. This means that the possible development will be accounted for, but it will not be predicted. (Svennevig, 2001)

As the study will investigate the techno-economic viability and climate impact, of an infrastructure project, the hypothesis will be established by assessing past developments of other past infrastructure projects. Furthermore, it will be assessed how these infrastructure projects can be developed, even though they are unattractive in the beginning.

An investigation, which will function as the observed facts, will be established. This investigation will consist of a scenario development, which will establish the different possible future phenomenon's. These scenarios will be established through literature review, and their uncertainty will be established through a sensitivity analysis. These scenarios techno-economic viability and emission reductions will then be modelled, to establish that which can be categorized to be observations. These observations can also be viewed as quantitative data.

The scenarios thereby establish quantitative results, which together with the hypothesis, can be used to infer a possible future phenomenon. A future phenomenon which is the techno-economic viability and GHG emission reduction of a PtX plant, as well as the possible approach to how the PtX plant might be established. Figure 2 shows visually how all the approaches in this study fits together, in order to infer the possible techno-economic viability, the emission reduction of the PtX-plant and the possible approach to ensure the PtX plant's establishment.

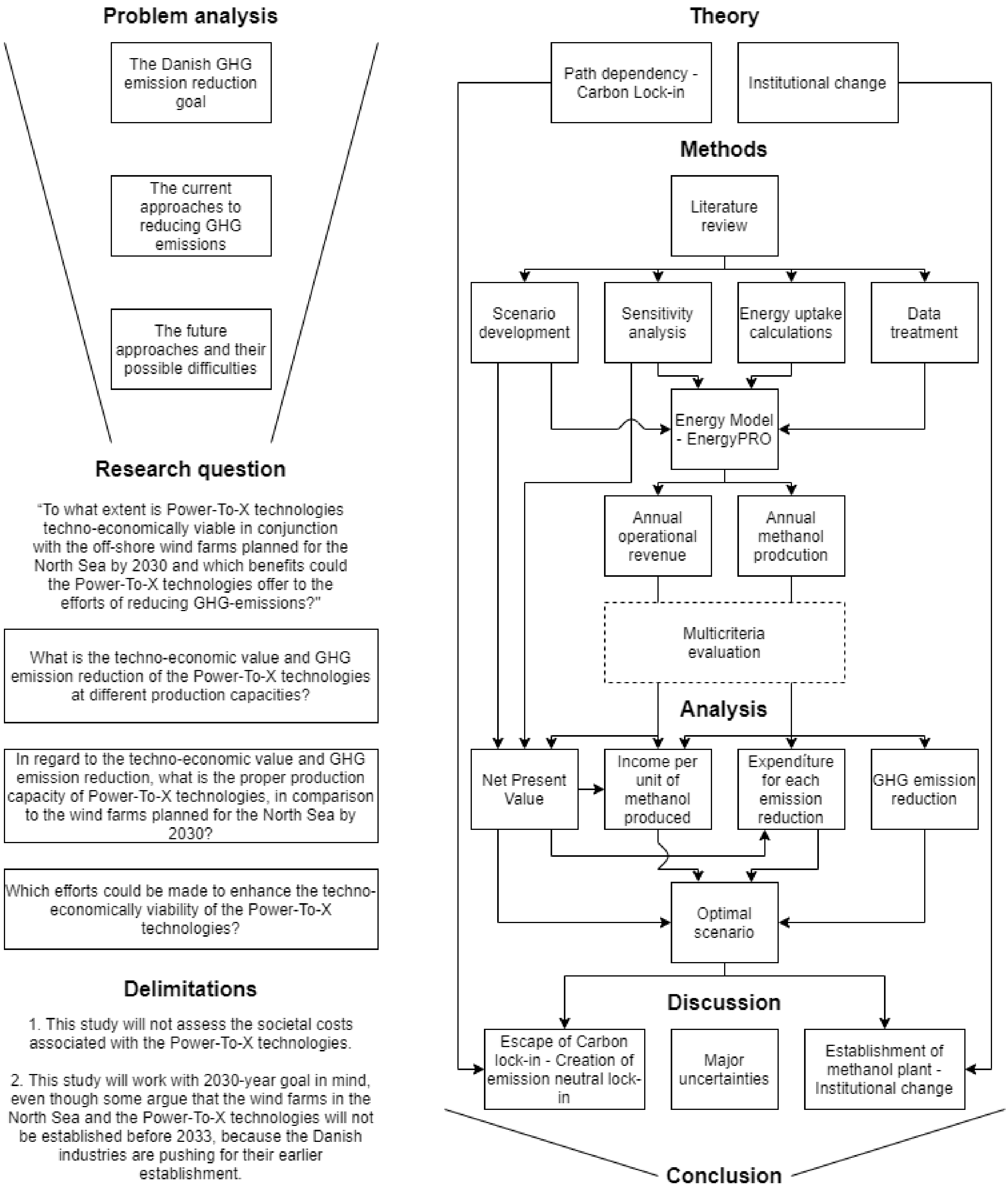

Figure 2 – Illustrates the flow of the report and how the different sections of the report fit together.

7 THEORY

In this chapter, the theory regarding path-dependency and institutional change, will be explained. These theories are important as they anticipate the development of the techno-economic viability of the PtX plants, but also suggests how one might solve potential issues.

7.1 PATH DEPENDENCY - CARBON LOCK-IN

Path dependency describes that, decisions made in the past may influence the possible choices which are available in the future. Even though some of the consequences created by the past decisions are not desirable in the present, the decisions have been made, and has shaped the present world. To exemplify, in the past when the trams were established, they were dimensioned to fit horse carriages. The railroads were then dimensioned accordingly to the tram's dimensions, consequently meaning that the railroads dimensions were designed based upon the horse carriages. The negative consequence of this, is that now larger goods are being transported, goods which dimensions does not fit the dimensions of the rail roads, making it impossible to transport these goods through railroad. As the establishment of the railroad infrastructure is so widespread, it is hard and too costly to convert to newer and more optimal railroad dimensions, as well as to change all the train carts so they can drive on the tracks. This is the reason why the less optimal infrastructure is continuously developed. This means that when largescale infrastructures are well-established, making it extremely hard and costly to replace or transition away from, a *vendor lock-in* is created. A vendor lock-in is when a customer or consumer is dependent on the products or services from a specific vendor and cannot switch without substantial costs or a decrease in prosperity. In this context, it is hard to predict the future and thereby predict what may be optimal, but it is necessary to establish qualified guesses to how the world will develop in the future. If an estimation of future trends and phenomenon's is established, it will be possible to understand how future facilities and technical infrastructures should be developed in the future, so a vendor lock-in is avoided. (Sundstrom et al., 2000)

Previously built fossil fuel-based heavy equipment has made it hard to invest in newer technologies, such as marine diesel-powered ships, where the associated oil supply companies have been well developed and are already established, which makes it hard and costly to switch away from. The same problem appears for the rest of the heavy-duty transportation sector, as well as the industry, service, and agriculture sector. This means that even with Denmark's current aspirations to switch over to green energies, parts of the industry across different sectors have achieved a *carbon lock-in*, as it will require significant investments for them to transition to green energies. It is defined as a *carbon lock-in* because it would require a significant cost for the industry to transition, or a significant drop in prosperity for the whole society if the use of fossil fuels were immediately seized, thereby creating a system where the society is reliant on emitting GHG. A lock-in is typically established through the availability of technologies, the determining politics and the interactions between technologies and politics, the interaction can be described as a techno-institutional complex (TIC). (Sundstrom et al., 2000) TIC emerges through large technological systems, such as in energy production, distribution, and consumption, these systems should be understood as a whole system where there is a larger connection between the social contexts of private and public institutions. Note that when TIC arises it becomes extremely complex to change a system, as politics are determined by opinions, which may be influenced by the companies which are persistent in maintaining their current approach, as it would otherwise be costly for them to transition to another system – e.g., a green energy system. (Unruh, 2000)

This means that when a *carbon lock-in* occurs together with TIC, it becomes extremely hard to start and/or accelerate a transition to green energy technologies, as the price of the transition influences the political willingness for change.

7.2 INSTITUTIONAL CHANGE THEORY

Institutional change was chosen as a theory to establish an overview of what initiatives that should be taken, in order to escape the carbon lock-in, as it has been theorized that the transition from fossil fuels will meet a lot of opposition from technologically entrenched companies.

Through the PA it was established that PtX might be a suitable technology to unroot the technologically entrenched companies, as it is compatible with the majority of the heavy industry's technology, which means PtX will only compete against the present major fuel sources. This means that the transition will not have to completely rethink and rebuild the heavy industry. This also means that to make the transition easier, the PtX follows the path, which was determined in the present, which means even PtX technologies are path dependent. If being path dependent allows Denmark to escape the carbon lock-in easier, it is clearly not the wrong approach, even though it might be a less optimal approach or create unforeseen problems in the future.

The study intends to investigate techno-economic viability of PtX technologies, in order to establish the magnitude of the resistance against PtX technologies as a consequence of the costs associated with the transition. Furthermore, the study intends to investigate how much these costs impacts the escape from the carbon lock-in, by assessing how much CO_2eq emission reductions is created through PtX.

Through the institutional change theory, the most probable approaches to incentivizing the transition to utilizing PtX fuels, without creating major opposition, will be mapped. This must be done by making solutions that directs the desired development, by going the least against existing institutions, thereby taking account for the techno-institutional complex.

In the theory of institutional change, institutions can be described as structures or social mechanisms which determines the behavior of corporations, organizations, or individuals. This means that the institutional frameworks govern the method to obtaining fuels for the heavy industry. To understand how the frameworks govern, the different institutions need to be clarified, as well as how these institutions affect choices. (Scott, 2014) The three commonly accepted institutional pillars are:

- Regulatory institutions (Government legislation)
- Normative institutions (Social Judgement)
- Cultural-cognitive institutions (Personal Conscience)

(Scott, 2014)

The regulatory institution is supposed to alter behavior through indirect or direct regulation sanctioned through legislation. This regulation can either prohibit one from certain activities by the threat of incarceration, indirectly affect behavior through positive incentives or penalize behavior through negative incentives. The indirect incentives can be tax breaks, subsidies, or tariffs, which alters the behaviors of the market actors in a certain direction. The negative incentives might be fines or tax increases. (Scott, 2014) In the case for PtX, the market could be incentivized to produce and use electrofuels, by taxing the CO_2 emitted from fossil fuels, subsidizing the production of each unit of electrofuels, or providing tax breaks to PtX plants.

The normative institutions affect behavior through either negative social sanctions or positive social reward. The social negative sanctions can be imposed through ridicule or the fear of ridicule, which influences the actions which the organizations, corporations and individuals take. The positive social reward may be affirmation or praise, which also impacts the actions of organizations, corporations, and individuals, and reinforces the decision to repeat the action. The normative institutions are decided by local social norms and obligations. (Scott, 2014) In the case for PtX, the consumption of electrofuels might be imposed through industry agreements in the heavy industry, by corporations excluding other corporations from business if they do not use electrofuels. Another example could be the introduction of carbon footprint traceability in products, through certifications, making the consumers exclude corporations with high CO_2eq emissions.

The cultural-cognitive institutions affect the behavior of individuals through their personal values, which is done through the individuals unconscious and conscious understanding of the individuals internalized values and the individuals' surroundings. This means that the cultural-cognitive institutions of an individual, may be altered through the education and enlightenment of the individual. The cultural-cognitive institutions affect the individual, through the individual's conscience and sense of pride through self-actualization of achieving what the individual thinks is noteworthy. (Scott, 2014) The utilization of electrofuels can be imposed by the individual choosing to purchase CO_2eq emission neutral fuels, instead of fossil fuels, as the shame or pride of either polluting or decreasing pollution for the planet pressures the individual. Although this depends on the individuals view on the CO_2eq emissions impact on the climate.

By creating an institutional change, the carbon lock-in will be escaped, but a carbon neutral lock-in will be created in its place. As of now, it can seem nonsensical to try to escape the carbon neutral lock-in as it would be costly and reestablish the imminent threat of global warming.

8 METHODS

In this chapter, the method for how the different data is found, will be described. Furthermore, the chapter will describe how this data has been treated, in order to establish the investigation occurring in this study. The chapter also describes how the investigation has been established, and what uncertainties there might be associated with the investigation and therefore the results of the study. This will be described, in order for the reader to understand how the study's approach creates the results of the study.

8.1 LITERATURE REVIEW

Literature review is an approach which is used to obtain information and knowledge about a subject from existing literature. Literature review is used for the enlightenment within a targeted subject, an enlightenment which is done through credible sources of information. Furthermore, it is an approach which enables a researcher to gather empirical data from existing literature, if deemed reliable. (Rienecker et al., 2012)

In literature review, the credibility and reliability of the literature at hand, is created by reviewing where the data and/or information from the literature originates. The review is done by categorizing the literatures knowledge within two categories: *primary*- and *secondary literature*. (Rienecker et al., 2012)

Primary literature is knowledge and data, in the form of statements, calculations, empirical data and publications, which originates from the direct source. This means that primary literature is knowledge and data concerning a specific subject, which originates from the parties who are responsible for the collection of the initial data and the initial explanation of the specific subject. (Rienecker et al., 2012)

Secondary literature is knowledge and data which is derived from the *primary literature*. This means that secondary literature is knowledge and data which has been collected from the direct source, then relayed or reinterpreted, and then published again. (Rienecker et al., 2012)

Literature review is used in this study, to ensure that the most credible sources are chosen for the establishment of the core problem this study is investigating, as well as for finding the data needed to establish a reliable model. Multiple source's data and knowledge have been disregarded, as they consisted of secondary literature and primary literature was required to create a reliable study. But there were instances where the secondary literature's origin/author were deemed credible and the secondary literature were therefore used in this study, but the use of secondary literature was kept to a minimum. Furthermore, some of the use of secondary literature was used in parts of the study which was of lesser importance.

8.2 SCENARIO DEVELOPMENT

There are different methods to estimating future trends and phenomenon's, at different levels of uncertainty and complexity. To create an estimate for the techno-economic viability and an estimate for the Greenhouse Gas (GHG) emission reduction of the Power-to-X (PtX) plant, which might get established simultaneously with the wind farm in the Northern Sea by 2030, the method for scenario development will be utilized.

Scenario development is one of the methods to estimate phenomenon's, problems, or opportunities, which might occur in the future.

Scenario development is suitable as the year of the PtX-plant's establishment is almost a decade into the future, and scenario development enables the study to achieve a high level of confidence. In connection with utilizing a scenario development, there will occur a complexity of the study, which will mitigate the uncertainty of the study (Ash et al., 2010).

The complexity of the study arises as there are many inputs which will be used in a mathematical model, and all these inputs are necessary to ensure the model contains many real dynamics making the model reflect reality as much as possible. As many of the inputs are variables, the study consequently becomes more uncertain. It is also this uncertainty and complexity, which is the reason for why this study establishes scenarios instead of predictions, as the future development would be too unpredictable. In contrast to predictions, the intent of scenarios is not to find the most plausible future phenomenon, but to find the possible development which might occur in the future (Ash et al., 2010). This also means that the intent of this study is not to find the most plausible development, but the development which might occur, then through institutional change find a way to make the wanted development more plausible.

The scenarios will be established through qualitative data, which creates a narrative as to why the certain technologies are chosen. The chosen technologies quantitative data will then be used as inputs in the model. The specific scenarios and their complexity and uncertainty will be described in the following subsections. Furthermore, an approach to mitigate the uncertainties of the scenario development, will be described in section 8.4.

8.2.1 The expected development

In this study it is expected that the wind turbine farm in the North Sea will be established, as it is expected that the PtX-plant will be established in conjunction with the wind turbine farms, and not without them.

When investigating the area, in which the North Sea wind turbine farm is expected to be established, it becomes apparent that there are other wind turbine farms planned to be built or is already build in the vicinity. Through literature studies, the capacities, properties, and lifetime expectancy of these other wind turbine farms have been found. These wind turbine farms are:

- Horns Rev 1 – 160MW (Built)
- Horns Rev 2 – 209.3MW (Built)
- Horns Rev 3 – 406.7MW (Built)
- Thor – 800-1000MW (Planned)

(Appendix B)

Through an assessment of the lifetime expectancy, it becomes apparent that both Horns Rev 1 and 2 will be decommissioned before the year 2030, which means that they will be excluded from this study. As Horns Rev 3 is still in commission and Thor has been built, by the year 2030, these wind farms are expected to be in operation simultaneously with the wind farms North Sea I, II and III. (Appendix B) This means, that this study will not only utilize the capacity of the North Sea wind turbine farms, but also the wind farms in the vicinity, as these wind turbine farms could be connected to the PtX-plant. As the exact capacity of Thor has not been determined, it is expected to be the maximum amount, as it is expected that power producing companies will want to fully utilize the area's nominated capacity.

Through literature studies the expected electricity cost for each unit of power, has been found. The electricity price has been calculated by a consultant company. The company has taken account for the investment, operations, and maintenance cost, then compared it to the power production during the wind farms lifetime expectancy and summed up the minimum price they must demand to become profitable. (Appendix B) It is this price which will be utilized in the study's model, when the PtX-plant receives power from the wind turbines.

The literature studies also found the wind farms' turbines hub height and their lifetime expectancy.

Table 1 below summarizes the wind turbine farms, which will be included as electricity producing units in the scenario, as well as their expected electricity price and nominated rate of power, hub height and lifetime expectancy.

Table 1 - Indicates the predetermined wind turbine farms properties (Appendix B)

Wind farm	Expected average electricity price [DKK/kWh]	The wind farms rate of power [MW]	Wind turbine hub height [m]	Lifetime expectancy [Year]
Horns Rev 3	0.77	406.7	105	25
Thor	0.4	1000	135	30
Nordsøen 1	0.4	1005	135	30
Nordsøen 1	0.4	1005	135	30
Nordsøen 1	0.4	1005	135	30

Note, that it is expected that the PtX plant will be connected in the vicinity of the wind farms, so that the PtX plant does not have to pay tariffs for purchasing power from the electricity grid.

8.2.1.1 Uncertainties

One of the uncertainties which arises with utilizing a fixed electricity price, which barely makes the wind turbines profitable, is that the owners of these wind turbines might want to create a profit. If that is the case, there will be production hours where the wind turbines would rather sell the electricity to the spot market, than to sell it to the PtX-plant. This mean that the PtX-plant would either shut down its production or take on the added economic costs which is associated with the methanol production, as explained in section 9.1.5. With this cheap source of electricity, which will be used in the model, the PtX-plant might appear more profitable than what it might be in reality. The model will try to mitigate the uncertainties associated with the fixed power prices, by making the PtX-plant compete for the cheap power with the electricity demand of DK1, at spot price levels.

Another uncertainty is the lifetime expectancy, as wind turbines might have a shorter or longer lifetime expectancy, than what is predicted. But this uncertainty might be small, as the amount of wind turbines averages out the lifetime expectancy, making the wind turbines average lifetime expectancy equal the predicted lifetime expectancy.

The values from table 1 will be utilized in conjunction with the different scenarios, which will be established.

8.2.2 The DAC – SOEC plant scenario

In the DAC – SOEC plant scenario, three technologies will be utilized in combination with each other, forming a methanol plant, which will be used in the energy model described in section 8.5. The technical and financial parameters from this scenario will be used in the power to methanol calculations, which will be modelled as a part of an energy system. The technologies which are a part of the scenario is:

- Direct Air Capture (DAC)
- Solid Oxide Electrolyzer Cell (SOEC)
- Methanol Synthesis plant

DAC - The DAC technology utilizes electricity to run a fan, which ensures a flow of air from the atmosphere, into a contactor device. In this device, the air is forced through a filter, which absorbs the CO_2 from the rest of the air. The filter can absorb the CO_2, because the filter is made from a polymeric material which can chemically bind the CO_2 to the filters surface, because the filter has amine functional groups[2]. This process will run for a few hours, as a result the filter will become saturated with CO_2, thereby the desorption phase can be initiated so the pure CO_2 can be extracted. In the desorption phase, vacuum is applied to the filter assisting with the desorption. While the vacuum is applied, the filter is heated to between 85-100^oC. The heat is applied with a low temperature heat source, such as hot water. The CO_2 which is extracted from the filter, reaches purities between 98-99.9%. (Energistyrelsen, 2021b)

SOEC – The SOEC technology utilizes electricity to electrochemically split the reactants, this is done by conducting a power current through two electrodes, one electrode is for oxidation the other for reduction. The two electrodes are separated by an electrolyte, in the case of the SOEC technology the electrolyte and two electrodes consist of a ceramic material, but there are other technologies where they do not. The reactants in SOEC can be H_2O or CO_2 which is fed in a gaseous form to the negative electrode, where the reactant is split, either to $2H_2$ and O_2 or $2CO$ and O_2. These reactions occur as the reactants are split the oxide ions are conducted through the electrolyte, the ions travel from the negative electrode to the positive, a reaction caused by the induced electric field. These oxide ions recombine as gaseous oxygen, creating either the dihydrogen or carbon monoxide. (Energistyrelsen, 2021c)

Methanol synthesis plant – The methanol synthesis plant is a technology which combines the dihydrogen and carbon monoxide, heating the solution to between 200-300^oC and pressurizing the solution to between 3.5-10MPa. This creates an exothermic reaction, which means energy is released from the reaction, an energy release corresponding to 91[kJ/Mol]. The released energy is recycled, meaning that the energy uptake of the methanol synthesis plant becomes very small. Through this process, the methanol is produced with a high purity, with a minor amount of side products. (Klerk, 2020) Due to the properties of the methanol synthesis plant, it is assumed that the energy uptake of the methanol synthesis plant is so small, that it can be considered negligible, meaning it will be neglected from the energy calculations.

In the DAC – SOEC plant scenario, the technical and financial parameters of the DAC and SOEC technologies has been found through literature studies. The DAC and SOEC parameters are respectively given by the technology data catalogues *Industrial Process Heat* and *Renewable Fuels*, published by the Danish Energy Agency.

The DAC, SOEC and methanol synthesis plant's technical and financial parameters will in this scenario be combined, in order to calculate the methanol plant's technical and financial parameters. This will be done

[2] Amine functional groups are organic compositions which contain a nitrogen atom, these amine functional groups can easily fixate CO_2. (Dehghanpour, 2020)

instead of using the *methanol from power plant* technical and financial parameters, which is also given in the technology data catalogue *Renewable Fuels*. This approach has been chosen, as the *methanol from power plant* given by the DEA, is assumed to have technology contents which are similar to the DAC – SOEC scenario because the electricity uptake for each unit of methanol produced, is similar to the calculated electricity uptake of the SOEC – DAC scenario. This can be seen on table 3, in section 8.3. This approach was chosen, as utilizing the parameters from the *methanol from power plant*, would not reflect the technical and financial parameters, which is associated with the different carbon dioxide source, that is used when a combination of Post-Combustion (PCC) and SOEC technology is used. As a result, this study is able to separate the technical and financial parameters associated with the different technologies used in the DAC – SOEC and PCC – SOEC scenario, which cannot be done if the *methanol from power plant* is utilized. Thereby the study is able to compare the two carbon capture technologies influence on the techno-economic viability of the methanol plant, as well as the different plants impact on the CO_2eq emission reductions.

The reason why the technical and financial parameters of the DAC – SOEC and Post-Combustion – SOEC scenarios are different from each other, is that the energy uptake per unit of carbon dioxide captured is different from each other. This means that the technical capacities proportions of the hydrogen and carbon dioxide production differs between the two scenarios. These proportion differences entails that the two scenarios will produce different amounts of fuel per unit of electricity consumed, but also that the size of the plants will differ.

In order to account for the methanol synthesis plant, in both the DAC-SOEC and PCC-SOEC scenarios, the economics of the methanol synthesis plant for each unit of methanol production capacity, will be calculated by comparing the DAC-SOEC scenario to the methanol plant given by the DEA. The calculation of the methanol synthesis plant will be done by calculating the cost of the capacity needed for the DAC and SOEC technologies to produce each unit of methanol. The cost of the methanol synthesis plant was then derived, by subtracting the cost of the DAC-SOEC technologies from the methanol plant given by the DEA. As a result, the cost of a methanol synthesis plant for each unit of methanol produced is derived, this can be added to both the DAC-SOEC and PCC-SOEC scenarios, depending on each of their different production capacities.

View section 8.3, to read how the electricity required to produce 1MWh of methanol is calculated, and how the capacity of the plant is derived from the electricity uptake. The calculations will be based upon the technical and financial parameters found in connection with the DAC – SOEC and PCC- SOEC scenarios. The methanol synthesis plant consumes almost no electricity in comparison to the carbon capture and hydrogen production, which is why this energy uptake of the methanol synthesis plant is neglected from this study (Energistyrelsen, 2021c). Furthermore, view section 8.3.1 to read how the proportions of the DAC – SOEC and PCC – SOEC scenarios are calculated, based upon the electricity uptake.

The reason for establishing the DAC– SOEC scenario is to investigate the techno economical costs, when utilizing a carbon capture technology which can extract an amount of CO_2, only limited by the amount in the atmosphere. Theoretically allowing for an unlimited production of fuel, as the subsequent combustion of the fuel emits the CO_2 back into the atmosphere, consequently making the whole process carbon emission neutral. The reason for using the DAC technology in conjunction with the SOEC technology, instead of other electrolyzer technologies such as alkaline electrolyzers, is that SOEC technologies have the highest recorded efficiency in converting a unit of hydrogen from electricity (Energistyrelsen, 2021c).

The technological parameters of this scenario are defined by the parameters published by the Danish Energy Agency. These technical parameters will be used in the methanol calculations in section 8.3. The properties for DAC, SOEC and methanol synthesis plant are given on table 2 in section 8.2.4.

8.2.2.1 Uncertainties

There are many uncertainties associated with the DAC – SOEC scenario, which makes is hard to state that the outcome of the scenario will reflect the future development.

One of the main uncertainties associated with DAC – SOEC scenario is the technology readiness of both DAC and SOEC is low. As of the year 2021, there are no large-scale plants utilizing DAC or SOEC technologies. All current plants are small scale experimental facilities, which are not yet economically viable or designed for large scale production, to match the competition on the market. (Energistyrelsen, 2021b & Energistyrelsen, 2021c) It is therefore necessary to stress that there are huge uncertainties with the Danish Energy Agency's projection that the costs will decrease by the year 2030. Financial parameters which will be utilized in this model.

For both the technologies there are many varieties, some technologies might yet be developed, and some may be unknown as the technologies might be developed in secret to secure patent rights. Furthermore, there are many varieties to the operational parameters, all which influences the efficiency of the methanol production. It is therefore unknown whether the technological and financial parameters of the DAC – SOEC scenario actually utilizes the optimal technologies as a consequence resulting in inaccurate calculations in the model, as the technologies parameter may be over- or underestimated.

Another uncertainty is that a DAC – Alkaline scenario will not be developed, which is unfortunate as possible benefits of alkaline electrolyzers then cannot be compared to the SOEC. This means that there will be a part of the PtX technologies possible techno economic viability and CO_2eq emission reduction which will be left uncovered. Using alkaline electrolyzers in a DAC scenario, instead of SOEC, was delimited from due to the time constraints of the study.

As previously described in the overall scenario method, the intent of scenarios is not to state what will happen but give an estimate of what might happen in the future, thereby enabling some measures to be predetermined based upon the results of this scenario.

Another uncertainty for this scenario, is that the investment cost of the cables to the methanol plant is not included, as well as the method of transporting the methanol to the consumers.

Another uncertainty is, that there might be many varieties of creating methanol, which will be left uncovered in this study.

The sale on the excess oxygen produced as a biproduct of the methanol production has not been included in this scenario, even though oxygen can be sold as a product to the chemical-, steel- and cement industry. (Energistyrelsen, 2021c) As a consequence, increasing the techno-economic viability of the methanol plant. Which means that an aspect of the techno-economic operation of the methanol plant will not be included, as a result potentially lowering the techno-economic viability of the methanol plant.

8.2.2.2 The efficiency of the heat input

As hot water ranging between 85-100^{o}C can be used a heat source for the desorption process, this hot water is expected to be utilized due to its simplicity. Because hot water is chosen as a heat source, an electric boiler is chosen as the means for heating the water in the methanol calculations. This means that an efficiency equal to that of an electric boiler, is used to calculate the extra electricity consumption which is created as a result of the necessary heat input. An electric boiler has been chosen, as it is simple and can be easily integrated as a component in the process. Furthermore, an electric heating unit has been chosen because it allows the carbon capture process to utilize electricity produced by renewable sources, such as wind turbines, instead of fossil fueled boilers.

The flaw of this approach is that heat pumps could be used as a heat source, instead of electric boilers, as a result consuming less electricity per ton CO_2 pulled from the atmosphere.

8.2.3 The Post-Combustion Carbon Dioxide Capture – SOEC plant scenario

The Post-Combustion (PCC) – SOEC scenario is similar to the DAC – SOEC scenario, utilizing three technologies in combination with each other, forming another type of methanol plant than in the DAC – SOEC scenario. The technical parameters from this scenario, will also be used as a part of the power to methanol calculations, which allows the scenario to be modelled as part of an energy system. The technologies in this scenario are:

- Post-Combustion carbon capture (PCC)
- Solid Oxide Electrolyzer Cell (SOEC)
- Methanol Synthesis plant

Post-Combustion CC – Is a technology which can be established in conjunction with existing CHP plants, biogas plants, cement kilns amongst other combustion plants and industries, which collects the CO_2 from the emitted gasses. The technology works by cycling the flue gases through a scrubber, which will quench the flue gas to between 30-40°C and scrub the flue gas from pollutants, allowing for a better extraction of the CO_2. Afterwards the cleaned flue gas is cycled through an aqueous solution containing amine functioning groups, which fixates the CO_2 in the solution. The solution saturated with CO_2 is then transferred to a desorber, which releases the CO_2 by applying heat to the solution. The heat source is steam pressurized to 3-5 bars which is injected into the desorber at 130-150°C, water temperatures which are achievable through an electric boiler[3], similarly to the DAC – SOEC scenario. (Energistyrelsen, 2021b)

SOEC & **Methanol Synthesis plant** – The SOEC and methanol synthesis plant will also be used as a part of the Post-Combustion scenario, to construct the methanol plant. These technologies are the same as explained in section 8.2.2 and will not be described again in this section.

The parameters for the Post-Combustion – SOEC scenario has been found the same way as the DAC – SOEC scenario, through literature studies. The parameters originate from the Danish Energy Agency's technology data catalogue *Industrial Process Heat* and *Renewable Fuels*.

The Post-Combustion scenario will be established to investigate the techno economic viability and CO_2eq emission reductions of a methanol plant, which acquires CO_2 from centralized carbon emission sources, which makes the power uptake per unit of CO_2 captured smaller, as well as reducing the investment costs. The intent of the Post-Combustion scenario is to establish knowledge about whether or not it is economically viable, to utilize point emission sources which emits CO_2 regardless, to produce electrofuels. As the methanol produced displaces the use of fossil fuels, the methanol will be calculated as an emission reduction.

[3] Water pressurized at 3-5 bar has a boiling point at approximately 133-151°C (InfoTables.com, 2021)

In this scenario there will not be a limit on the CO_2 potential, which is needed for the production of the electrofuels, but it is relevant to investigate the potential amount of CO_2 which can be extracted from point sources.

8.2.3.1 Uncertainties

It is uncertain which type of point source will be utilized to extract CO_2 to produce the methanol, but it would be best if the sources were CO_2 emission neutral, so the sustainability of the process is indisputable. Although, it is arguably better to utilize CO_2 from non-emission neutral sources, which would otherwise emit CO_2, if this could displace the use of fossil fuels. Therefore, the CO_2 source is questionable. Furthermore, it is questionable if the methanol production can be calculated as an emission reduction, even though it displaces fossil fuels, as the CO_2 source is cement kilns amongst other sources.

This study does not investigate the amount of CO_2 potentials each year, which means that it is uncertain whether there is enough CO_2, which can be captured at point sources, to fulfill the modelled methanol plants need at the different capacities. The explanation of the different capacities will be given in section 8.3.1.

Furthermore, this study does not investigate the cost associated with transporting CO_2 to the methanol plant. This creates an uncertainty for the techno-economic viability, as the transportation of CO_2 might increase the cost for the methanol plant.

Furthermore, the costs associated with transporting and distributing the methanol out to the consumers, has not been included in this study. But this cost is also not included in the price for the fossil-fuel based methanol. Which means that the distribution of methanol is assumed to be an added cost, which is absorbed by the consumers.

8.2.4 Technical and financial parameters

On table 2 the technical and financial parameters of the DAC, PCC, SOEC and methanol synthesis plant technologies are given, these parameters will be used in the calculations of the energy uptake per unit of methanol produced in section 8.3. The financial parameters of the methanol synthesis plant will also be included in the table, even though the methanol synthesis plant's value has been derived by subtracting the values calculated in section 8.3.1, from the methanol plant given by the DEA, meaning that the values of the methanol synthesis plant will be given before the calculation method has been fully described. This was done to ensure the table will not be repeated, filling unnecessary space in the report.

Table 2 - Indicates the properties for SOEC and Carbon Capture technologies in the year 2030 (Appendix B)

Properties	**Direct Air Capture - 2030 Values**	**Post-Combustion Capture - 2030 Values**	**Properties**	**SOEC - 2030 Values**	**Methanol Synthesizer**
Specific investment [DKK/ton CO2 output/hour]	45,000,000	20,250,000	Specific investment [DKK/MW]	4,500,000	7,278,571.76
Fixed O&M [DKK/ton CO2 output/hour]	2,250,000	600,000	Fixed O&M [DKK/MW/year]	135,000	(Omitted)
Variable O&M [DKK/ton CO2 output]		18.75	Variable O&M [DKK/MWh]	Electricity price	
Startup cost [DKK/startup/(ton CO2 output/hour)]		187.5	Efficiency of electricity to hydrogen output	79	
Life-time Expectancy [Years]	20	25	Life-time Expectancy	20	20
Heat input [kWh/kg-CO2]	2	0.72			(Omitted)
Electricity input [kWh/kg-CO2]	0.32	0.025	Electrical Efficiency	79%	(Omitted)
	(Energistyrelsen, 2021b)			(Energistyrelsen, 2021c)	

8.2.5 Capacity scenario

The DAC – SOEC and Post-Combustion – SOEC scenario is categorized as the two main scenarios, from which other sub scenarios have been derived. In order to establish the capacities of the methanol production plants, a capacity scenario has been established.

In the capacity scenario the capacity of the DAC – SOEC and Post-Combustion – SOEC methanol plant will be established based upon the wind farms capacity, of which the methanol plant will be established in conjunction with. It is the methanol plants energy uptake which will be matched correspondingly with the wind farms located in the North Sea, an energy uptake which has a methanol output depending on the main scenario's methanol plant type. The output will be calculated in section 8.3.

The capacity scenario will vary the energy uptake capacity of the methanol plant, thereby the production capacity, in a sequence matching the capacity of the wind farm in the Northern Sea. This sequence will be given as a percentage of the wind farms capacity, resulting in the corresponding energy uptake of the methanol plant. The sequence is:

- 100% - of nominated Northern Sea wind farm capacity.
- 80% - of nominated Northern Sea wind farm capacity.
- 60% - of nominated Northern Sea wind farm capacity.
- 40% - of nominated Northern Sea wind farm capacity.
- 20% - of nominated Northern Sea wind farm capacity.
- 0% - of nominated Northern Sea wind farm capacity.

The capacity scenario will be established in correspondence with the wind farms in the North Sea, as it is expected that the established methanol plant will not be built without the wind farms, therefore it is expected that the energy uptake capacity of the methanol plant will also rely on the wind farms capacity.

Furthermore, the capacity of the methanol plants energy uptake is given as a percentage, to enable the methanol plant capacity to scale proportionately with the wind farms. Thereby the optimal capacity proportions between the wind farm and the methanol plant might be found, allowing the impacts of the proportions of the methanol plant and wind farms to be distinguishable regardless of the wind farms capacity.

8.2.5.1 Uncertainties:

The disadvantages of having high differences between the variating capacities, is that the impacts which can be observed at smaller levels will not be enlightened. This means that there could be optimal capacities for the methanol plants, which lies between the different percentage points of the capacity. But the intent is not to find the exact optimal capacity, but to develop a scenario which suggests what the best proportions between the methanol plant and wind farms capacity could be.

8.2.6 Power source scenario

In the power source scenario, the two main scenarios power consumption will rely on two different sources, either the wind farm power production or the cheapest supplier on the power market.

This scenario will be created by changing the operational strategy in the energy model, which will be explained in section 8.5. This will consequently mean that the methanol plant can only produce when power is delivered from either of the two sources.

Only the wind farms – In this scenario the methanol plant is only allowed to produce when receiving power from the wind farms, or when the methanol plant can acquire power through the down regulation market or special down regulation market. As explained in section 8.5.3.4, the reason that the methanol plant can use special down regulation and normal down regulation power, is that the trend shows that the special down and normal down regulation power originates from wind turbines. It is therefore in this study assumed that special down and normal down regulation will originate from wind turbines, which means that instead of down regulating wind turbines, the methanol plant will scale up its consumption matching the excess power which might otherwise have been switched off.

Market – In this scenario the methanol plant is allowed to produce as long as it can acquire electricity from the power markets. This means that the wind farms in the North Sea is competing in the regular market, in order to deliver power to the methanol plant. The wind farms in the North Sea are assumed to have the advantage that they are directly connected to the methanol plant, which means that the methanol plant does not have to pay any fixed tariffs for receiving power through the grid. If the methanol plant receives power through the market, the plant has to pay the fixed tariffs on top of the electricity price. Furthermore, it is expected that power obtained through the Nord Pool spot market, can originate from solar power, other wind turbines, hydro power, other countries, or CHPs.

The power source scenario has been developed in order to investigate the impact, the operational strategy has on the techno-economic viability of the methanol plant and the CO_2eq emission reduction of the methanol plant.

8.2.6.1 Uncertainties

In the technology data catalogue, *Renewable Fuels* published by the Danish Energy Agency, the SOEC technology is described as a unit which works best with continuous operation. (Energistyrelsen, 2021c) This means that a scenario which only utilizes the wind farms in the North Sea might be impossible without future technological breakthroughs, as wind power is a fluctuating power source, as it relies on the wind speeds to produce power. (Appendix B)

Another uncertainty with the power sources, is the market price. This scenario does not account for the increase in power prices, which would be a result of the increased demand, as explained by the market dynamic supply and demand.

8.2.7 Sale of excess heat scenario

The last scenario is rather simplistic. It has been assumed that the methanol plant has been connected to a district heating grid, allowing the methanol plant to sell excess heat. In this scenario it is assumed that the methanol plant is connected to the district heating grid at no extra cost, and all the heat is assumed to be consumed. Examining the investment cost of coupling the methanol plant to the district heating grid is not within the scope of this project. This approach has been chosen to make this scenario simple and do-able within the time frame of this study, as the scenario would otherwise have been impossible.

In this scenario it is assumed that heat output of the methanol plant corresponds to 10% of the methanol output. When comparing this scenarios heat output to the *power to methanol plant* heat output given by the Danish Energy Agency, the heat output of this scenario is 60% less per unit of electricity consumed. (Energistyrelsen, 2021c)

The price of the excess heat, which is sold to a public supply company, is expected to be equivalent to the heat price of the cheapest district heating supplier in Denmark. This price was found to be: 410.94 DKK/MWh. Which is based on the heat price of Videbæk District Heating. Furthermore, the price is expected to be fixed, as public heating supply companies operates with fixed tariffs. (Forsyningstilsynet, 2020)

As the price is fixed, the sale of excess heat scenario will not be included in the energy model but will be calculated afterwards and added to the annual operational income of the methanol plant.

The sale of excess heat scenario has been established in order to investigate the significance the sale of excess heat might have on the techno-economic viability of the methanol plant. It is not expected that the sale of excess heat scenario will have any CO_2eq emission reductions, as it is expected that the sale of the excess heat will displace other renewable heat sources such as electric boilers or heat pumps.

8.2.7.1 Uncertainties

The largest uncertainty in this scenario, is that the investment cost for connecting the methanol plant to the district heating plant is not included. To further improve this scenario, it would be beneficial to investigate where the methanol plant should be established, weighing whether it should be placed near a district heating grid, and then calculate what the costs for the connection would be. Then adding the cost to the investment cost of the Net Present Value calculation.

8.2.8 Summary of scenarios

All of the scenarios will be done in a combination of each other, which means that if an extra scenario is added, the different combinations will result in a doubling of the number of variations of the different scenarios combinations. This means that the study's iterations increase exponentially with the number of scenarios added to the study. These scenarios can be seen in appendix B, as well as their inputs.

8.3 Calculation for the energy uptake of methanol production

In this section, the electricity uptake per unit of methanol produced will be calculated for both the methanol plants, which technology contents has been described in section 8.2.2 and 8.2.3. To reemphasize, the reason for calculating the energy uptake for each methanol plant, was to isolate the impact the CO_2 source has on the efficiency of the system. This energy uptake will then be used in the energy model.

Through literature studies the properties of the different substances, which is going to be utilized in the methanol plant and in the CO_2eq emission reduction calculations, has been found and summarized in appendix B. The properties include the lower and higher calorific values of the fuels, the density of the substances, the atomic compositions and the substances molecular weight calculated from the atomic compositions, and the atoms molecular weight. The approach to calculating the molecular weight can be seen on equation 1.

$$M_{Total} = Amount \cdot M_{Substance} + \cdots + Amount \cdot M_{Substance}$$ *Equation 1*

To calculate the energy uptake of the methanol plant per unit of methanol produced, the mass of substances needed for the reaction needs to be established, as each of these substances requires energy to be extracted from each of the sources. The substances needed to produce the methanol in each of the plants, has been established to be CO_2 and H_2, due to the technological properties determined in the DAC – SOEC and Post-Combustion – SOEC scenario. To determine the mass of the substances needed for the production of methanol, a reaction formula for the chemical equilibrium has to be established. The chemical equilibrium reaction formula for H_2, CO_2, and CH_3OH can be seen on reaction 1.

$$2CO_2 + 4H_2 = 2CH_3OH + O_2$$ *Reaction 1*

Equation 2 shows how the amount of the substance in 1kg methanol is calculated. The weight of the methanol is necessary to establish the amount of substance in the compounds needed to create the methanol. The weight of the methanol has been chosen due to its mathematical scalability, in conjunction with the capacity of the methanol plant, which will be calculated later in this section.

$$n_{CH3OH} = \frac{m_{CH3OH}}{M_{CH3OH}}$$ *Equation 2*

Through reaction 1 and the amount of substance in the methanol, the amount of substance of CO_2 and H_2 needed for the reaction, can be calculated. This calculation is done by dividing the amount of substance in the 1kg of methanol, with the number of methanol molecules in the equilibrium reaction formula. The amount of substance in the desired compound is then found, by multiplying with the number of compound molecules in the reaction formula which is needed to create the methanol. This can be seen on equation 3.

$$n_{compound} = \frac{n_{CH3OH}}{x_{CH3OH}} \cdot x_{compound}$$ *Equation 3*

The mass of the CO_2 and H_2, which is needed to produce 1kg of methanol, can be found by multiplying the molecular weight with the amount of substance, as can be seen on equation 4. The mass of the compounds will be used, as applying volumetric parameters is prone to errors in the chemical calculations, as the density of compounds changes disproportionately at different temperatures.

$$m_{compound} = M_{compound} \cdot n_{compound}$$ *Equation 4*

Now the electricity input, which is needed to produce each compound needed for the production of the methanol, can be calculated. This is done by utilizing the technological parameters given for each technology, which has been accounted for in section 8.2.4.

The parameters of the Carbon Capture (CC) plant specifies that a certain mass of CO_2 can be created by an electricity and heat input. The electricity and heat input needs to be recalculated, so that they become equivalent to the inputs needed, to produce the mass of CO_2 utilized for the production of the methanol. The electricity input equivalent to producing enough CO_2 for the production of methanol, is calculated by multiplying the mass of CO_2 needed for the methanol, with the input parameter specified for the CC plant. This approach is also utilized for the calculation of the heat input equivalent to producing enough CO_2 for the production of methanol, but the heat input will also be divided by the efficiency of the heat production unit. These calculations can respectively be seen in equation 5 and 6. As the heat input will be created by an electric boiler, the heat input will be transferred to the electricity consumption. As a result, the CC part of the methanol plant only utilizes electricity as an energy source.

$$E_{e \to CO2} = m_{CO2} \cdot E_{e-Input} \qquad \textit{Equation 5}$$

$$E_{Heat \to CO2} = m_{CO2} \cdot \frac{E_{Heat-Input}}{\eta_{e-Boiler}} \qquad \textit{Equation 6}$$

The electricity input needed to produce enough H_2 for the production of methanol, is calculated by calculating the energy content in the mass of H_2 needed for the production of methanol. Then dividing the energy content with the efficiency of the SOEC plant's ability to electrolyze power into a resulting amount of H_2. This calculation can be seen in equation 7.

$$E_{e \to H2} = \frac{m_{H2} \cdot \Delta H_{H2}}{\eta_{SOEC}} \qquad \textit{Equation 7}$$

As a consequence of the two main scenarios technologies, the whole methanol plant relies on electricity to produce methanol. This electricity consumption can be calculated through the sum of equation 5, 6 and 7, which is given as equation 8.

$$E_{e \to CH3OH} = E_{e \to CO2} + E_{Heat \to CO2} + E_{e \to H2} \qquad \textit{Equation 8}$$

The results of these calculation can be found on table 3.

Table 3 - Indicates the electricity demand needed to produce each MWh methanol (Appendix B)

Electricity:		
SOEC and Direct Air Capture of CO2 [MWh]	1.61	$Equation\, 8$
SOEC and Post-Combustion CO2 capture [MWh]	1.24	
DEA methanol plant [kWh]	1.64 (Energistyrelsen, 2021b)	

The electricity input needed to produce each unit of methanol, will be given as the unit [MWh] to make the energy uptake easier to compare with the sale of methanol in the model, which is given as [DKK/MWh]

8.3.1 The proportion calculations of the CC and SOEC part of the methanol plant

The proportions of the CC and SOEC part of the methanol plant needs to be calculated, as it is these two parts of the plant, which contributes to the investment, operations, and maintenance costs. The proportions of the CC and SOEC part of the methanol plant, will be calculated as capacities matching the financial parameters given on table 2 in section 8.2.4. Furthermore, the methanol production capacity will be calculated. This production capacity will be used in combination with the electricity consumption, as inputs for the methanol plant in the energy model.

As mentioned in section 8.2.5, the capacity of the methanol plant relies on the percentage of nominated capacity in regard to the capacity of the wind farms in the North Sea, which means this capacity and percentage also specifies the proportions of the CC and SOEC part of the methanol plant.

The proportion of the CC part of the methanol plant, is found by dividing the total electric uptake capacity of the methanol plant, with the energy uptake required to produce one equivalent unit of methanol, then multiplying with the mass of CO_2 required to produce the equivalent amount of methanol. Note the uptake capacity is determined by the capacity scenario. This calculation can be seen in equation 9.

$$C_{CO2\rightarrow Out} = m_{CO2} \cdot \frac{C_{WTG} \cdot C_{\%}}{E_{e\rightarrow CH3OH}} \qquad \textit{Equation 9}$$

The proportions of the SOEC part of the methanol plant, is found similarly to equation 9, but instead of multiplying with the mass of CO_2 required to create the methanol, the equation will be multiplied with the energy uptake required to produce the utilized amount of H_2. The calculation can be seen in equation 10.

$$C_{H2\rightarrow Out} = E_{e\rightarrow H2} \cdot \frac{C_{WTG} \cdot C_{\%}}{E_{e\rightarrow CH3OH}} \qquad \textit{Equation 10}$$

The methanol plant's production capacity can be given by dividing the electric uptake capacity of the methanol plant, with the energy uptake required to produce one equivalent unit of methanol, then multiplying with the calorific value of methanol. This calculation can be seen in equation 11.

$$C_{CH3OH\rightarrow Out} = \Delta H_{CH3OH} \cdot \frac{C_{WTG} \cdot C_{\%}}{E_{e\rightarrow CH3OH}} \qquad \textit{Equation 11}$$

When used in conjunction with the parameters of the technologies, given on table 2 in section 8.2.4, the values derived from equation 9 and 10 will be used to calculate the investment, operations, and maintenance costs. Equation 11 will be used to calculate the methanol production capacity associated with the established electrical uptake capacity. Note that the capacity of the methanol synthesis plant is equivalent to the output capacity of methanol for each hour.

Through the calculations the capacities of the different scenarios were found, the capacities are given on table 4.

Table 4 - The production capacity for the SOEC plant and Carbon Capture plants (Appendix B)

			Wind Turbine Norminal Power [MW]:	4421.7
Capacity in comparison to the wind turbine park's norminal power [%]	**Direct Air Capture [ton]**	**Electricity uptake - Direct Air Capture [MW]**	**Equivalent SOEC [MW]**	**Output of methanol - Direct Air Capture [MWh]**
100%	639.50	1496.56	2925.14	2741.86
80%	511.60	1197.25	2340.11	2193.49
60%	383.70	897.93	1755.09	1645.11
40%	255.80	598.62	1170.06	1096.74
20%	127.90	299.31	585.03	548.37
0%	0.00	0.00	0.00	0.00
Capacity in comparison to the wind turbine park's norminal power [%]	**Post Combustion [ton]**	**Electricity uptake - Post Combustion [MW]**	**Electricity uptake - Equivalent SOEC [MW]**	**Output of methanol - Post-Combustion Capture [MWh]**
100%	830.15	624.50	3797.20	3559.27
80%	664.12	499.60	3037.76	2847.42
60%	498.09	374.70	2278.32	2135.56
40%	332.06	249.80	1518.88	1423.71
20%	166.03	124.90	759.44	711.85
0%	0.00	0.00	0.00	0.00

8.4 Sensitivity analysis

A sensitivity analysis is an approach used to determine how the values of the parameters, which are used in an investigation, affects the overall results of the investigation. The intent of a sensitivity analysis is generally to investigate how much uncertainty, the input parameters create for the investigation. (Pichery, 2014)

In this study, the sensitivity analysis will be used to vary the input parameters applied in this study's model, which is based on the scenarios, to predict the scope the modelled scenarios results might be within. This means that instead of relying on the model to find one exact result for the scenarios future development, it is expected that there will be an uncertainty, therefore this uncertainty will be applied in the model, enabling the study to find a range which the study's scenario results might be within. Utilizing this approach might mitigate the uncertainty associated with the whole study, as more varieties of the real worlds impacts is accounted for. The results which are expected to be found through the model, and vary due to the uncertainty, is the techno-economic costs of the scenario and the emission reductions of the scenario.

The input parameters, which are uncertain and that will therefore be used as parameters for the sensitivity analysis, are:

1. The Nord Pool Spot-Market Prices
2. The power consumption of DK1
3. The wind speed at the area of the wind turbines
4. The down regulation market prices

5. The down regulation market volumes
6. The special down regulation market prices
7. The special down regulation market volumes
8. The methanol prices
9. The discount rate

The parameters for point 1-8 will all be bundled together in one overall category, which will be the year in which the data is measured. It is then the year in which the parameters are measured which will be changed, as it is the year of measurement which determines the uncertainty of the parameters for point 1-8. The reason that it is the year which determines the uncertainties, is that the measured values for the parameters, is historic data which is tied to each hour in the full course of the year in consideration. This means that the values in the parameters of point 1-8 are values measured on an hourly basis, which makes them a sequence of interchangeable values. As they are historic values, they are dependent on each other. Thereby making it the year's varying data which should be investigated as a whole.

The years which will be used in the sensitivity analysis, will be 2017, 2018 and 2019. The reason for choosing these years, is that the wind farms which will be established in the North Sea, will be connected to the Danish power grid through the power market area DK1. DK1 is connected to Norway which has large hydro power reservoirs, which due to their capacities, partly determines the Nord Pool Spot-Market prices in each respective year. The years were chosen, due to the years status of respectively being a wet, dry, and normal year (Ellefsen, 2020, Karagiannopoulos, 2018 & Norwegian Ministry of Petroleum and Energy, 2021). The wet, dry, and normal year impacts the spot market price, as higher or lower amounts of precipitation in the corresponding years, causes the hydro reservoirs to either become to full or empty, resulting in either lower or higher bids on the spot-market, depending on the levels of water in the reservoirs. (Karagiannopoulos, 2018) This impact is expected to play a large role in the viability of the methanol plant, which is why these years will be used as an uncertainty for the markets yearly impact on the methanol plants operational revenue, creating an uncertainty for where the operational revenue might be within, due to the uncertainty of the energy markets and the consumption on an annual basis.

The discount rate will also vary, due to the uncertainties associated with the world markets, which might heavily impact the viability of the methanol plant when comparing it to other potential projects.

The discount rate of 8% was chosen as one of the discount rates in the sensitivity analysis, as the DEA used this discount rate to calculate the NPV of the wind farms in the North Sea, which the PtX will be established in conjunction with.(Energistyrelsen, 2020b) The discount rate of 3.5% was chosen as the maximum discount rate, as the Danish Ministry of Finance in 2021 suggested to use this discount rate for future socio-economic assessments.(Finansministeriet, 2021) The discount rate of 5.75% was chosen, as it is the median of these two values.

8.5 Model setup

In order to investigate the techno-economic viability of a PtX-plant, as well as the CO_2eq emission reduction caused by it, a simulation model of the setup established in the scenarios will be utilized. This model will utilize the scenarios established in section 8.2, as input parameters for the model's technical setup. For the PtX-plant, which the scenarios have established to be a methanol plant, the energy conversion rate will be based on the conversion rate established in the methanol energy calculation from section 8.3. The parameters which determine the production of the wind farms located in the North Sea, as well as the methanol plant, were briefly mentioned in the sensitivity analysis, but will be explained in-depth in this section.

8.5.1 Choice of modelling tool

EnergyPro was chosen for the execution of this study's model, as the tool allows the user to perform detailed financial and technical analysis's, of an energy system setup defined by the user. The tool allows the user to perform timeseries modelling, where operations of different technologies at different periods of time can be calculated, making the investigation reflect reality in a larger degree. The investigation can through EnergyPro reflect reality in a larger degree, because the dynamics of a complex energy system can be included in the model. (EMD, 2021b) Although, these dynamics can only be established, if the user knows how to establish a model containing the right dynamics, thereby making the model reflect reality. These dynamics can be the operation strategies of the whole energy system setup, the impacts of the weather, the consumption profiles, the market impacts etc. (EMD, 2021b).

EnergyPro allows the user the freedom to choose how the energy system setup should operate, thereby allowing for tailored models which can be used to investigate whatever the researcher intends. This makes EnergyPro suitable to model the methanol plant, and surrounding dynamics impacting the methanol plants production. (EMD, 2021b)

8.5.2 Wind power production

The wind power production in the Northern Sea will through EnergyPro, be modelled by inserting the capacity of the wind turbines totally nominated power, as a production unit in EnergyPro. These wind turbine production units will be split into two different wind turbine production groups, which are determined by the estimated power price and technological properties of the wind turbines. These two wind turbine groups will be Horns Rev 3 and the wind farm North Sea – Thor, as they in the wind capacity scenario development have two different power prices. The wind turbines in the North Sea are assumed to be similar to the wind turbines in Thor, which means that their technological properties can be grouped together.

The next parameter which the grouped wind power production units relies on, is the wind speeds which the wind turbines are affected by, at different hours of the year. These wind speeds will be given as an hourly value, in a sequence which matches the power prices in the power market. These matching sequences of hourly values are called timeseries. Utilizing the wind speeds timeseries in combination with the power markets prices is important, as these wind turbines permission to transmit to the power grid and subsequent production, will be determined by the markets power prices.

The timeseries for the wind speeds determines when the wind farms produce, but the wind speeds also determine how much power the wind farm is producing. The wind farms produce a different amount of their nominated power capacity at different wind speeds, which can be accounted for through a power generation curve. This power generation curve specifies the wind turbine's ability to produce a factor of their nominated capacity at different wind speeds. For each wind turbine model, this power generation curve is different. But for simplicity, it is assumed that all of the different wind turbine models power generation curve is the same. In this study, a power generation curve has been extracted from another simulation tool called Power Factory and will be used as this energy model's power generation curve. The original power curve cut-off at wind speeds reaching above 25[m/s], but this was extended to 30[m/s] as the wind turbine models used in this model, is expected to be operational at these wind speeds. This new cut-off was established by the source of which the wind power capacity scenario was derived. This power generation curve can be seen on figure 3.

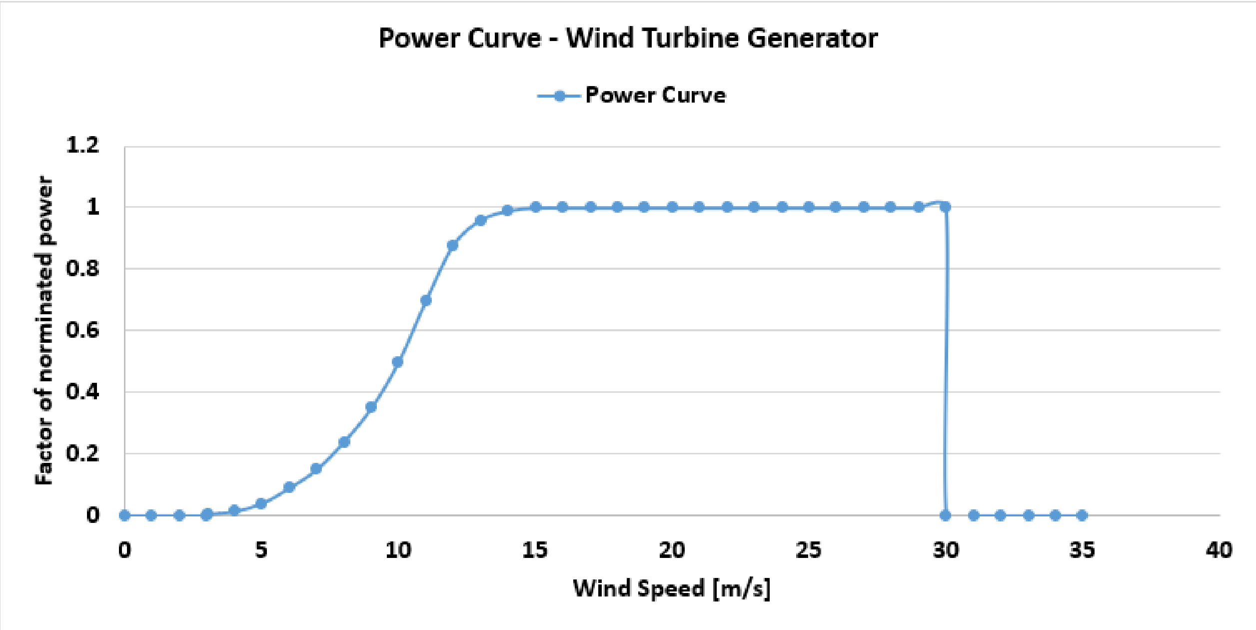

Figure 3 – Illustrates the factor of the wind turbines nominated power, which the wind turbines can produce at different wind speeds. (Appendix B)

The wind farms power generation will in EnergyPRO be calculated by multiplying the wind speeds at different hours, with the corresponding factor in the power generation curve. Thereby the power generation for the specific hour is calculated, whether the power might be used to supply the demand in the model, depends on the operational strategy. In this model, the condition for activation is tied to the prices in the power market.

The frequency of different wind speeds each year are indicated on figure 4, which together with figure 3, implicates how much the actual wind power generation varies.

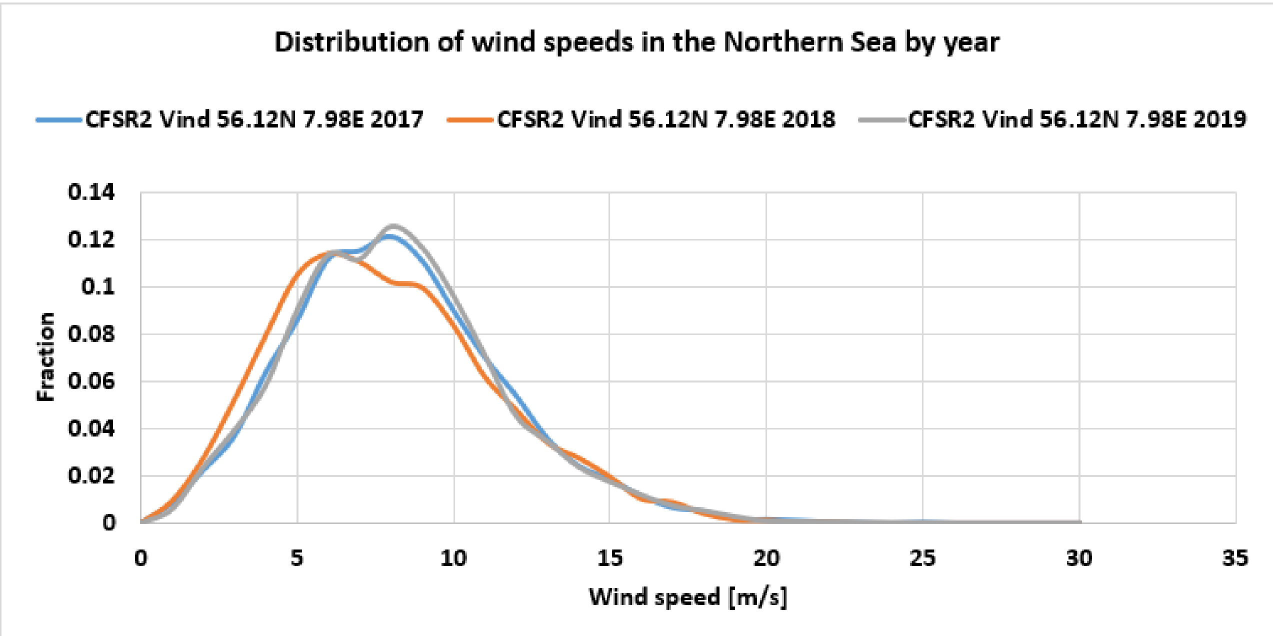

Figure 4 – Illustrates the distribution of the occurrences of different wind speeds in the Northern Sea by year. (Appendix B)

Note that the prices for the wind turbines power production were determined on table 1, and these values will be used as fixed operational expenditures each time the wind farms power will be consumed in the model.

8.5.2.1 Uncertainty

Thor and the North Sea wind turbine farms might not be similar at all, as the tender process might lead to other wind turbines being established, than what is planned for the future in this study. Therefore, the model of wind turbines might be different, consequently changing the technological parameters.

8.5.3 Carbon Capture, SOEC and Methanol production

The methanol plant, which has been established in the scenario in section 8.2.2 and 8.2.3 and which energy conversion rate has been calculated in section 8.3, will be included in this model as it is the focal point of this study's investigation. This methanol plant will be modelled in EnergyPro, by inserting an electric boiler as a production unit, which shall reflect the methanol plant, as EnergyPro does not have a PtX production unit. The electric boiler will consume electricity and produce a heat output in the model, but instead of viewing this as a heat output, it will be categorized as the energy content in the methanol produced. The electricity consumption of this boiler will be defined as the electricity uptake, which has been defined in the capacity scenario, and the methanol output will be defined as the value given through the calculation of equation 11. Due to the technical properties defined in each of the methanol plant scenarios, there will be no other source contributing to the production of methanol, but electricity.

The electricity can be obtained through the Nord Pool spot-market, the wind turbines in the North Sea, the down regulation market, or the special down regulation market. Note, that when the PtX plant utilizes the power markets, the electricity will originate from the power grid, the choice of market only determines the price which the methanol plant obtains the electricity.

Due to fact that the methanol plant can utilize three different markets, and EnergyPro only allows the plant to be operated through one market, three versions of the methanol plant will be created in the model. The first production unit, which will reflect the part of the methanol plant which can obtain power from the Nord Pool spot market, will be dimensioned with capacities specified by the capacity scenario. The second and third production unit, reflecting the part of the methanol plant which can produce based on electricity from the down and special down regulation market, will respectively produce based upon the power volumes available in the down regulation market and special down regulation market. This production will be calculated in the model, by inserting the power volumes as timeseries in the electricity input capacity, of production unit two and three. The output will be calculated by dividing the timeseries values with the electricity uptake needed to produce each unit of methanol. To ensure that the production in the methanol plant does not exceed the specified capacity, due to varying capacities of production unit two and three, the input and output of production unit two and three will respectively be subtracted from the first production unit's input and output production capacities. Equation 12 shows how the output capacities of production unit two and three, which reflect the methanol plant, is calculated:

$$Output = \frac{Timeseries(PowerVolume)}{E_{e \to CH3OH}} \qquad \textit{Equation 12}$$

Equation 13 shows how the power output in the main production unit, reflecting the methanol plant, will be calculated. In the model these timeseries variables will be called Down Regulation Power Volume (DRPV) and Special Down Regulation Power Volume (SDRPV)

$$Output = C_{CH3OH \to Out} - \frac{T(DRPV)}{E_{e \to CH3OH}} - \frac{T(SDRPV)}{E_{e \to CH3OH}} \qquad \textit{Equation 13}$$

Note that the input in the main production unit will be subtracted with the input values in the second and third production unit, which varies depending on the DRPV or SDRPV timeseries values.

Through this approach, the impact of the different market's prices on the methanol plants viability might be found.

Note the methanol plant must operate as a whole, therefore the operation for production unit two and three of the methanol plant, is dependent on the operation of the main methanol plant.

8.5.3.1 Uncertainties

Modelling the markets through the previously mentioned method, creates an uncertainty for the study's result, as the approach does not completely reflect reality. The approach does not reflect reality, because the model creates a situation where the methanol plant will always get awarded the power volumes available on the down regulation and special down regulation market. This will not be the case, as there on the down regulation market will be other competitors, who might bid lower to get awarded the power volumes available on the down regulation market – this could be heat suppliers with heat pumps or electric boilers. For the special down regulation market, the methanol plant might not get awarded all the volumes as the market works through pay-as-bid, which means that with more parts of the whole energy system becoming more electrified the competition for winning these bids might be tougher and they might drive the price for special down regulation up – higher prices means that the methanol plant will benefit less.

8.5.3.2 Spot-Market

The spot market is a power exchange, where the majority of Danish power producers and power suppliers sell and purchase power. In the Nord Pool spot-market, the power producer provides a volume of power they want to produce at a given price. The power suppliers provide an estimate of how much power they expect to purchase in the given hour. The Nord Pool spot exchange then calculates how much power which needs to be produced each hour in the next 24 hours, based on the volumes provided by the power suppliers, the cheapest power producers needed to provide the power volumes are then awarded the production responsibility. Each power producer activated is awarded the same price per unit of power delivered, a price which is equivalent to the price entered by the highest bidding power producer awarded the production responsibility. (Energinet, 2013)

In this study the methanol plant's purchase of power from the spot-market, will be reflected in the model by including the historic spot market prices as a timeseries for a whole year. The year which these historical prices is derived from is explained in section 8.4. In this model the power market is expected to be capable of delivering enough power to the methanol plant, at the given prices. This power will be transferred trough the power grid, which means that the fixed power tariffs will be added on top as an expenditure, but it also means that the source of power is untraceable in this study. The power which originates from the Nord Pool spot market, might be wind power, solar power, hydro power, or power from CHP's.

The methanol plant will buy the power from the spot market to cover its demand if it cannot be supplied by the wind turbines in the North Sea.

8.5.3.3 *Uncertainty*
When the methanol plant utilizes the spot markets power, it is uncertain whether this power stems from power producing units consuming fuels or other fluctuating power sources. If fuel power producing units is utilized the methanol production will be counterproductive to the point of the methanol plant.

The impact of the methanol plant's added power consumption, on the spot price, will not be investigated and is therefore not included in the model. The approach of using unchanged historical data with no price increase as the consumption increases, might cause uncertainties in the study's results, as the study therefore does not adhere to the laws of supply and demand[4].

8.5.3.4 *The relation between wind power, down and special down regulation*
Through literature studies, it has become apparent that the wind turbines in Northern Germany is often the cause for the need of down- and special down regulation, as the wind turbine production often exceeds the expected production. Tennet, which is the German Transmission System Operator (TSO), often uses the Danish special down regulation market to switch of Danish wind turbines, to stabilize the frequency in their transmission grid. (Dansk Fjernvarme, 2015)

In this study, it is assumed that it is counterproductive to switch off the Danish wind turbines, as the intent of the wind turbines is to extract kinetic energy from the wind to produce electricity. Therefore, it would be better to increase the consumption of a production unit somewhere, instead of switching of the wind turbines production.

This means that in this study's model, it is expected that in the future the methanol plant, or some other production unit, will get awarded the down and special down regulation power volume. If this assumption proves to be true, it will mean that the approach in modelling all the markets impact on the methanol plant might not be so inaccurate, as the methanol plant could be the prime candidate for storing excess electricity as produced fuel.

8.5.3.5 *Down regulation market*
The up and down regulation market is an exchange where power producers can provide frequency response services to the TSO, by declaring their willingness to either produce more or produce less, depending on the need of the TSO. Large-scale power consumers can provide frequency response services in the down regulation market, by consuming more power. In this market the price is defined by the highest of the activated frequency response services activated, and like the spot-market the price is the same for each unit of power. If the frequencies goes above or below a certain level, the Danish TSO utilizes this market to reestablish the frequencies to the desired levels, as the TSO through the up and down regulation market obtains control over the frequency response units. (Energinet, 2018)

In this study's model, only the down regulation market will be utilized, as the methanol plant is categorized as a large-scale power consumer and can therefore not contribute to the up-regulation market. The down regulation market will be reflected by inserting a yearly timeseries containing historical values for the power volumes available, in the calculations in equation 12 and 13. Furthermore, the prices for this electricity will also be given as a timeseries containing historical values, matching the power volumes purchased by the methanol plant. This means that when the methanol plant utilizes the volumes of power available in the down regulation market, the methanol plant will pay the down regulation markets prices for the electricity in that hour, instead of the Nord Pool spot prices. Note that if not enough power is

[4] One of the laws of supply and demand states that if the demand increases, the price will increase an equivalent amount. (Investopedia, 2021)

available in the down regulation market, the remaining power will stem from the next cheapest source which could be the spot market depending on the corresponding hours price.

8.5.3.6 Special down regulation market

The special down regulation market, which is another method for regulating the power frequencies without impacting the up and down regulation market, does not adhere to the normal price order. The special down regulation market work through pay-as-bid, which means that some power producer or consumer can decrease production or increase consumption, for a price only applicable to that producer or consumer. The special regulation of power is utilized by the TSO to manage technical problems in the grid, without affecting the up and down regulation market, causing other technical problems. (Energinet, 2018)

The special down regulation market will be reflected in this study's model similarly to the down regulation market, as described in section 8.5.3.5.

8.5.4 Electricity demand

As the methanol plant's capacity varies, depending on the capacity scenario, the methanol plant will not be able to consume all the electricity produced from the wind farms in the North Sea. To ensure that the model somewhat resembles the true power market's dynamics as the methanol plant's capacity vary, the power consumption of DK1 in 2030 will be established as a timeseries, to check whether the wind farms produced power can be consumed.

The electricity demand for DK1 in 2030, will be calculated by utilizing the historical data for DK1's power, then adding the expected power consumption increase, which can be expected towards 2030. This expected power consumption increase, might originate from the increase in the electric vehicle (EV) fleet and the Danish households replacing their fossil fuel-based heating units with heat pumps.

The timeseries containing the EV fleet's electricity demand, has been calculated by multiplying the average hourly EV demand, with a charging profile developed in the report *The Impacts of EV Charging on the Danish Energy System*. The average hourly EV demand was also obtained from the same report, but as the demand included the whole Danish energy system, it needed to be recalculated so that the EV demand matches DK1. This recalculation was done by splitting the EV power demand up per capita, then multiplying it with the number of citizens living within DK1.

The hourly electricity demand needed for the heat pumps in DK1, will be calculated by summarizing all the fossil fuel-based heat sources for the Danish households, then calculating the value per capita. This per capita value will then be multiplied by the number of citizens in DK1 and then divided by the coefficient of performance of a single house heat pump. This value will then be divided by the number of hours in the course of a year, giving the hourly average electricity consumption of heat pumps for households. This value will then be multiplied with a heat consumption profile for households, which has been obtained from EnergyPlan.

8.5.5 Sale of methanol

In this model, the sale of methanol was defined to be unlimited, in order to investigate the potential techno-economic viability and CO_2eq emission reduction of the methanol plant without any restrictions.

The methanol prices were based on methanol produced from fossil fuels, as it allows the study to investigate how the renewable methanol might fair against the existing markets methanol.

8.5.5.1 Uncertainty
No limit on the methanol demand might create some uncertainty, as the methanol produced in large quantities might not be easy to sell without a proper distribution network, which has not been researched in this study. Without a proper distribution network, the large amount of production of methanol might create a surplus in the market, leading to the plant having to sell the methanol at lower prices, making the methanol plant less viable.

8.5.6 Operating expenses
Besides the operating expenses associated with the market, there are other expenses.

The first two expenses are the start-up cost and fixed operational cost, these have been calculated by multiplying the scenarios capacities with the values given in table 2. The third operating expense is the variable cost, for each unit of methanol produced, this value is also given on table 5.

8.5.7 Model summary
Note that the operational strategy of the model depends on the power source scenario. Furthermore, the operational strategy specifies that the cheapest source of electricity will be used in the methanol plant, the power sources will be chosen through the algorithm provided by EnergyPro. This algorithm can choose the cheapest energy source for operation, if the demand is not covered, the algorithm will find the next cheapest energy source and so forth.

Figure 5 illustrates the setup of the model, where the timeseries will be used and the outputs which are expected as a result.

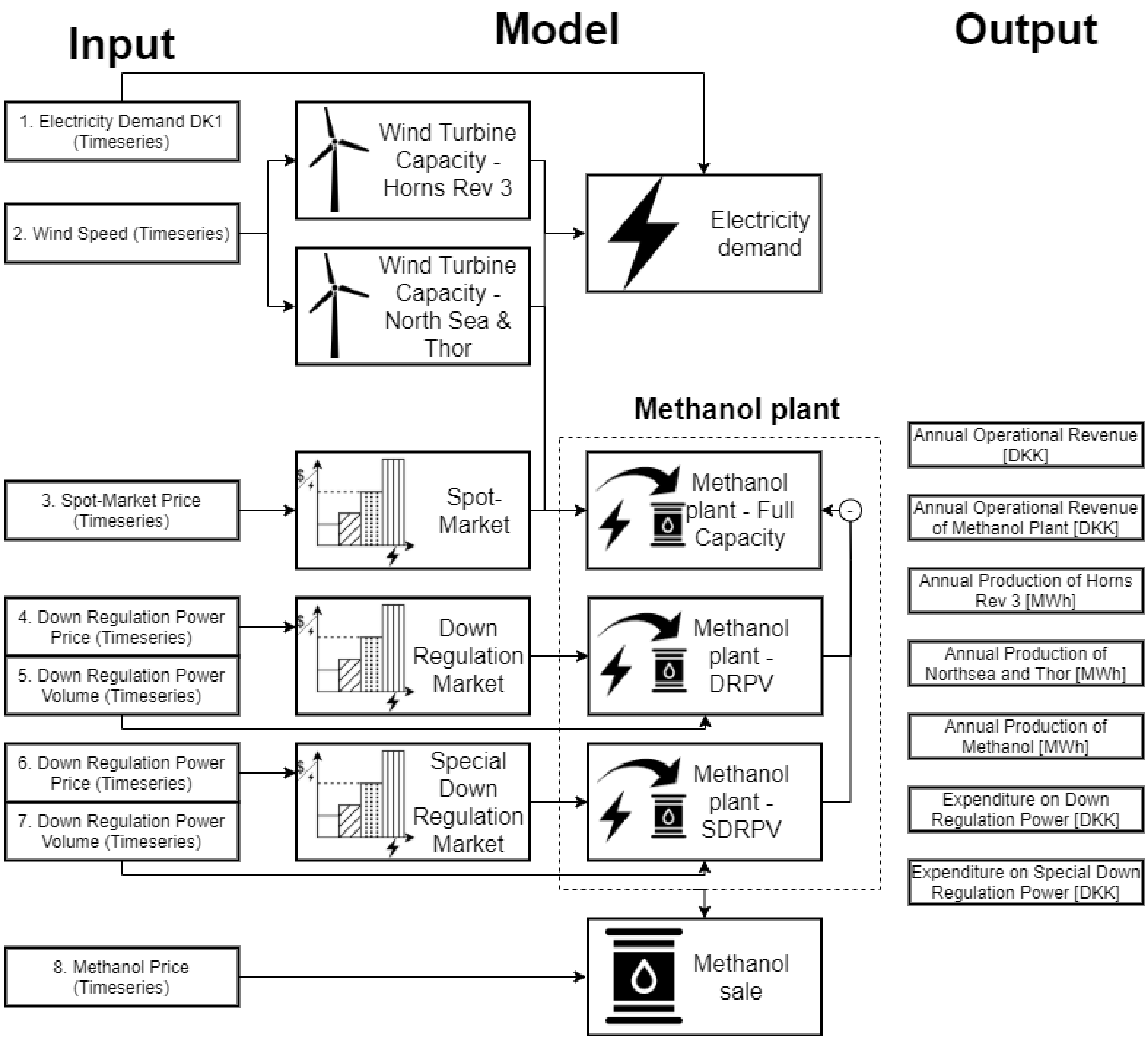

Figure 5 – Gives an overview of the entire energy model. It visualizes the inputs which will be used in the model, as well as the model in EnergyPRO. Lastly it visualizes the outputs which are expected from the model, which will be used in the analysis.

8.6 DATA TREATMENT

The following section will explain how some of the data was treated before it was inserted in the model. This will be done in order to create complete transparency in how the data was treated before it was inserted in the model, as it consequently impacts the results of the model.

When reviewing the different data sets containing the timeseries, which is going to be used in the modelling of the methanol plant, it was observed that there were missing values. The occurrences of the missing values were only observed once or twice in some of the datasets. In the instances where the missing data occurred, the rows were either entirely missing or some of the values were missing, resulting in an incomplete data for the entirety of the dataset’s corresponding year. To solve this issue, the timeseries missing timestamps were expanded accordingly and the missing values were then filled with the average value of the two values surrounding the missing value. When this occurred, the data was marked with a note explaining where the missing data occurred.

8.6.1 Northern Sea Wind Farms

The data used to create the expected development scenario, which contains the data of the wind farms, has been gathered from different consultancy reports developed by the request of the Danish Energy Agency.

The technical specifications of the wind farm Thor could not be found, therefore the technical property of Thor is assumed to be the same as for the other wind farms – North Sea I, II & III. This assumption seems plausible, as the capacity of Thor is similar to the North Sea wind farms, and Thor will be established a few years ahead in the same area. Therefore, it might be possible that Thor will create a pathway for the other wind farms, meaning that the same new wind turbines establishment will be tested at Thor, before establishing more capacity at the other areas.

The wind turbines cable dimensions and power losses will not be investigated in this study, as it would be too time consuming to calculate the losses of the cables. Furthermore, the best choice of cables would also have to be investigated, which also means that the location of the methanol plant has to be established. This enhances the uncertainty of the study's model, as there would in reality be a power loss between the wind turbines and the methanol plant.

8.6.2 Spot market prices

Every timeseries is dependent on the spot market prices, as these prices decides when different units produce, and the availability of the units is decided by the parameters within the confinement of the prices. As the spot-market prices are given as an hourly value, the remaining data must also be given as an hourly value.

The historical spot market prices have been gathered from the Nord Spot exchange, for each year corresponding to the sensitivity analysis. The fixed power tariff, which is imposed on the electricity price when it is transmitted through the power grid, is assumed to be 288[DKK/MWh] a number obtained from the Danish TSO (Energinet, 2013). This fixed tariff is added to each value in the spot-market prices timeseries.

8.6.3 Wind speeds

The timeseries containing the wind speeds, which were used as input in the model, were obtained through EnergyPro. These wind speeds were chosen, as their point of measurement, is located between the wind farms planned for the North Sea. The point of measurement is located in the following latitude and longitude: 56.12N and 7.98E.

The measurements of the wind speeds originate from CFSR2 data, which is satellite-based weather measurement, which has been reanalyzed – Hence the name *Climate Forecast System Reanalysis version 2* (CFSR2). The data is given as a timeseries, where the wind speeds are given as an average in the course of the measured hour. (NOAA, 2021)

8.6.4 Special down regulation prices and volumes

The special down regulation prices were obtained through a forwarded email, which contained the correspondence between an official from the Danish TSO Energinet, an email which can be seen in appendix A.

In appendix A, the average special down regulation prices, and volumes for the months January till October in 2020 is given. As the down regulation price of November and December is missing, this price is assumed to be the weighted average of all the special down regulation prices available. The weighted average is calculated by dividing the corresponding month's special down regulation power volume, with the average of all the months special down regulation power volume, thereby giving a factor signifying the weight which the months values contribute to the average value. This significance factor is then multiplied with the special down regulation power price, for each of the months, and then the average of these values is calculated. Thereby giving the weighted average special down regulation power price, which will be utilized for December and November. This calculation method can be seen in equation 14.

$$Weighted\ mean = mean\left(SDRPP_{Month} \cdot \frac{SDRPV_{Month}}{mean(SDRPV)}\right) \qquad \text{Equation 14}$$

This approach was chosen as it was expected that months with more special down regulation should have a greater impact on the value, as there are expected to be a bigger variety of bidders being awarded special down regulation through the pay-as-bid procedure, when a larger amount of special down regulation power volume is available. Thereby, the weighted average is expected to show a truer value for what the special down regulation might have been, as it prioritizes the months with more actively traded special down regulation power volumes.

The special down regulation power prices are extrapolated for each of the corresponding month's hours, so that a timeseries matching the rest of the timeseries is created, containing all the special down regulation power prices for each hour of the given month.

This timeseries will be used for each of the years investigated in the sensitivity analysis, as no other data for the special down regulation power prices were available at the time this study was conducted.

The timeseries containing the special down regulation power volumes, was found through the Nord Pool spot exchange. As was the data for the down regulation market's prices and volumes.

8.6.4.1 Uncertainty

Unfortunately, the special down regulation power prices do not reflect the actual special down regulation price, which is associated with the volumes traded in the different years, as these years have different dynamics in their energy systems and therefore different grid related issues which creates the special down regulation prices. But the prices are expected to give a somewhat accurate indication of the special down regulation markets influence, as they are used in combination with actual special down regulation power volumes measured in the years which is modelled.

8.6.5 Methanol prices

The methanol prices have been derived from a company called Methanex, which claims themselves the largest producers of methanol, supplying the Pacific Asia, Europe, North- and South America. (Methanex, 2020) The prices per unit of methanol were given as monthly values, which were extrapolated from each month's starting hour to its final hour, thereby giving an hourly timeseries which makes the values comparable to the other timeseries in the model.

Furthermore, the prices per unit of methanol was changed from mass to energy content, to make the values more comparable to the unit used in the *calculation for the energy uptake of methanol production*.

8.7 MULTICRITERIA EVALUATION

Multicriteria evaluation is a method, which can be utilized to compare different alternatives, which might be found as the best alternatives in different aspects. In the method, multiple criteria will be established as a way to evaluate the results of the study, on multiple aspects. Multicriteria evaluations might be used qualitatively or quantitatively, to create a basis for why one alternative might be the best. These criteria can be based on the intent of the study but can also be based on unforeseen developments, which were found during the study. Some of the criteria can be deemed more important than others, depending on the problem which is supposed to be solved. (Miljøstyrelsen, 2003)

In this study, the different alternatives will be the scenarios which has been established. Note that the sensitivity is the scope of which the scenario results might lie within, the scenarios will therefore also be evaluated based on their uncertainty. This means that the possible range of the whole scenario's results, which will be investigated through the sensitivity analysis, will be evaluated.

Through the multicriteria evaluation, the most techno-economically viable and CO_2eq emission reducing scenarios can be found. Furthermore, through this approach, the best of all the scenarios might be picked and suggested as a solution to the problem formulation.

8.7.1 Net Present Value

The Net Present Value (NPV) is chosen as a criterion, which will be used to assess the scenarios, as it accounts for the whole techno-economic viability of the methanol plant.

Net present value is a method used to calculate the current value of the cumulative future cash inflows and outflows, as well as the initial capital investment. The value calculated through NPV method, indicates whether the given project is profitable and can be compared to the NPV calculated for other projects, to establish which project might yield the greatest profit. This means that the NPV is used to investigate whether a project might be a viable investment. (Lund et al., 2010)

The NPV takes account for the diminishment of the future cash inflows and outflows actual buying power, by discounting the cash inflows and outflows. The discounting is done by multiplying the total cash flows, called the Net Payments (NP), with an annuity formula, which accounts for the impact of the discount rate (i) over a period of time (t). This formula can be seen on equation 15.

$$NPV = NP \cdot \frac{1-(1+i)^{-t}}{i} - Investment \qquad \textit{Equation 15}$$

In this project, there are different technologies with different lifetime expectancies, which needs to be accounted for, in order to make the different scenario's technologies lifetime expectancies financially comparable. The lifetime expectancy of the different technologies will in this study become comparable, by calculating each technology's full investment cost as an annual investment cost, then multiplying each annual investment cost with the whole project's lifetime expectancy. As the methanol plant depends on the establishment of the wind farms in the North Sea, the lifetime of the wind turbine farms is assumed to determine the lifetime expectancy of the whole project. Furthermore, the whole methanol plant is expected to be financed through loans, which means that the annual investment cost needs to be accounted for as annual repayments with interest. Note that the interest rate is given by the sensitivity analysis, which varies to check the impacts the discount rate, thereby the world economic situation, might have on the techno-economic viability of the methanol plant. The annual repayment calculation can be seen on equation 16.

$$AR = Investment \cdot \frac{i}{1-(1+i)^{-t}}$$ *Equation 16*

Through equation 15 and 16, it becomes apparent that to calculate true NPV associated with the whole methanol plant, the annual repayment of the whole project must be used instead of the capital investment, as it is probable that the methanol plant will be financed through loans. This means that this study's NPV is calculated trough equation 17, as utilizing loans means that there are future cash flows which goes into the investment, these future payments need to be accounted for through the annual repayment calculation method.

$$NPV = NP \cdot \frac{1-(1+i)^{-t}}{i} + Investment \cdot \frac{i}{1-(1+i)^{-t}} \cdot t$$ *Equation 17*

The operational income will be derived through the model, whereas the investment cost will be derived through the financial parameters associated with the capacities of the different scenarios. These financial parameters are given on table 5. These financial parameters have been calculated through the parameters of table 2 and table 4.

Table 5 - Indicates the financials at different production capacities (Appendix B)

					Post-Combustion Capture -Variable O&M [DKK/MWh]:	4.37
Capacity in comparison to the wind farms norminal power [%]	**PCC - Investment [DKK]**	**PCC - Fixed O&M [DKK/year]**	**PCC - Start-Up Cost [DKK]**	**Equivalent SOEC - Investment [DKK]**	**Equivalent SOEC - Fixed O&M [DKK/year]**	**Equivalent Methanol Synthesizer - Investment [DKK]**
100%	16,810,537,543.23	498,090,001.28	155653.1254	17,087,403,572.32	512,622,107.17	19,956,797,810.12
80%	13,448,430,034.58	398,472,001.02	124522.5003	13,669,922,857.86	410,097,685.74	15,965,438,248.09
60%	10,086,322,525.94	298,854,000.77	93391.87524	10,252,442,143.39	307,573,264.30	11,974,078,686.07
40%	6,724,215,017.29	199,236,000.51	62261.25016	6,834,961,428.93	205,048,842.87	7,982,719,124.05
20%	3,362,107,508.65	99,618,000.26	31130.62508	3,417,480,714.46	102,524,421.43	3,991,359,562.02
0%	0	0	0	0	0	0
"	**DAC - Investment [DKK]**	**DAC - Fixed O&M [DKK/year]**	**Equivalent SOEC - Investment [DKK]**	**Equivalent SOEC - Fixed O&M [DKK/year]**	**Equivalent Methanol Synthesizer - Investment [DKK]**	
100%	28,777,466,605.50	1,438,873,330.28	13,163,141,451.35	394,894,243.54	25906419030	
80%	23,021,973,284.40	1,151,098,664.22	10,530,513,161.08	315,915,394.83	20725135224	
60%	17,266,479,963.30	863,323,998.17	7,897,884,870.81	236,936,546.12	15543851418	
40%	11,510,986,642.20	575,549,332.11	5,265,256,580.54	157,957,697.42	10362567612	
20%	5,755,493,321.10	287,774,666.06	2,632,628,290.27	78,978,848.71	5181283806	
0%	0	0	0	0	0	

8.7.1.1 Uncertainty

There can be many uncertainties associated with calculating the NPV, one of the main uncertainties is the discount rate, as it is tied to the world's economy. The world's economy can be impacted or destabilized by so many factors tied to different events, which in the current time is unknown to anyone. As the project's lifetime extends many decades into the future, the chances for more destabilizing events to occur increases.

There are other uncertainties associated with the NPV, such as the NP, the lifetime expectancy, and the investment costs, but these uncertainties have been described in the development of the scenarios.

Note, the sensitivity analysis was created in order to mitigate the uncertainties associated with the discount rate and the operational revenues.

8.7.2 CO_2eq emission reductions

The annual CO_2eq emission reduction is chosen as a criterion, which will be used to assess the scenarios, as it is one of the main investigation points of this study. Note it is one of the main investigation points, as it is important to reduce the GHG emissions, to mitigate climate change.

In this study, the CO_2eq emission reductions are defined as the amount of CO_2 in the fossil fuels, which is displaced by the amount of fuel produced in the methanol plant.

Methanol is assumed to be used as a replacement for diesel, as methanol can be used in its pure form in both gasoline and diesel engines, if these engines are modified (Zhen, 2018). The methanol is expected to be used as a replacement for diesel, as the problem analysis suggests, that the internal combustion engine vehicles (ICEV) will be replaced by electric vehicles (EV) and that there are other sectors where the heavy industry vehicles rely on diesel which cannot be electrified as of now.

Even though the internal combustion engines efficiency changes depending on the fuel which is utilized (Zhen, 2018), the efficiency between the utilization of methanol and diesel is expected to be the same in this study. This means that the utilization of one energy unit methanol in an engine is assumed to equivalent to the utilization of one energy unit diesel.

Making the energy uptake equivalent means that the CO_2eq emission reductions caused by the diesel displacement, can be found by calculating the fuels CO_2 emissions per unit of energy utilized, then multiplying with the energy content of the fuel produced annually at the methanol plant. The calculation of the CO_2eq emission reductions can be seen on equation 18.

$$m_{CO2 \rightarrow Emitted} = E_{CH3OH \rightarrow Out} \cdot \frac{\left(\frac{m_{Fuel}}{M_{Fuel}} \cdot n_{Carbon} \cdot M_{CO2}\right)}{\Delta H_{Fuel}} \qquad \textit{Equation 18}$$

The carbon dioxide content in each energy unit of the different fuels, can be seen on table 6.

Table 6 - Indicates the Carbon dioxide content in each MWh fuel (Appendix B)

Fuel	Emission [ton CO2/MWh]
Methanol	0.23
Diesel	0.27

8.7.2.1 Uncertainty

There is an uncertainty associated with this approach, which is that in reality the energy uptake of a methanol internal combustion engine (ICE) is not equivalent to that of a diesel ICE.

The measured break thermal efficiency of a pure methanol-based engine ranges between 34-42%, depending on the chamber pressure and shaft rotations per minute. The measured break thermal efficiency of a diesel-based engine ranges between 26-40%, depending on the chamber pressure and shaft rotations per minute. (Zhen, 2018) This indicates that the CO_2eq emission reductions might be underestimated, because if the efficiency of the engines were included, the diesel engines using methanol would run more efficiently. As a consequence, there would be less energy uptake by using methanol, thereby furthering the diesel displacement.

Furthermore, the emission reduction is assumed to have a trade-off of 1:1, for each unit of energy consumed, but table 6 implies that this is not the case.

8.7.3 The income per unit methanol produced

The income per unit of methanol produced, has been chosen as a criterion, which will be used to assess the scenarios, as it allows the study to evaluate the worth which is created by each unit of methanol. This approach makes it possible to quantify the impact between the scenarios on a unit basis.

The income per unit methanol produced is calculated by dividing the NPV with the total energy produced in the methanol plant's lifetime, this approach can be seen in equation 19.

$$I = \frac{NPV}{E_{CH3OH \rightarrow Out} \cdot t} \qquad \textit{Equation 19}$$

This criterion is important because it shows the income per methanol production, which impacts the climate.

8.7.3.1 Uncertainty

It must be noted, that even if the income per unit of methanol is the highest for the methanol plant with the largest capacity, it might not be possible to invest in the scenario. It might not be possible to invest in the largest capacity scenario, because the initial capital investment cost is too high for anyone to afford the project.

8.7.4 The NPV per CO_2eq emission reduction

The NPV per CO_2eq emission reduction, has been chosen as a criterion, which will be used to assess the scenarios, as it will allow the study to evaluate the NPV for each climate impact associated with the scenarios. This approach makes it possible to quantify the climate impact between the scenarios on a unit basis.

The NPV per emission reduction, is calculated by dividing the absolute value of the NPV, with the emission reduction in the project lifetime, as can be seen in equation 20.

$$NPV\ per\ Emission\ reduction = \frac{|NPV|}{m_{CO2 \rightarrow Emitted} \cdot t} \qquad \textit{Equation 20}$$

8.7.4.1 Uncertainty

The optimal solution might be constrained by the other factors, so even if there is a scenario with the highest emission reduction per NPV, it might be constrained by the magnitude of the investment needed to establish the solution.

9 ANALYSIS

In this chapter, the results of the model will be presented in a concentrated format, consisting of plots, which will present the results in a format which follows the multicriteria evaluating. This chapter will describe the results implications. Furthermore, the chapter will find the optimal scenario through the multicriteria evaluation. The optimal scenario's results will then be compared to the theory of path dependency and the theory of institutional change. All the values of the results can be found in Appendix B.

9.1 MODEL RESULTS AND CALCULATIONS

The model results, derived from modelling the scenarios and the sensitivity parameters, which have been established through the data found through the literature studies, will be presented in this section of the analysis. All the scenario's results and their uncertainty created through the sensitivity parameters, will be presented as a whole, to establish an understanding of all the results. Thereby enabling full insight into the techno economic viability, and the CO_2eq emission reduction, caused by the suggested methanol plants.

The model results will be put into perspective, with the implications of the calculations for the energy uptake of the methanol production, the electricity and methanol price. This will be done, in order to establish a reason behind the results implications.

The different scenarios results will then be highlighted in the multi criteria evaluation in section 9.2.

9.1.1 Net Present Value

The Net Present Value's (NPV) for the different scenarios, at different capacities, and the impact caused by different sensitivity parameters, can be seen on figure 6. The different scenarios are implied by the colors of the dots, as well as the capacity increase along the x-axis. The uncertainty associated with each scenario, investigated through the sensitivity analysis, is implied by the range of the same-colored dots at the same capacity. The NPV of these scenarios is given by the value on the y-axis. Each colored dot, representing the scenarios, is explained in the figure's legend.

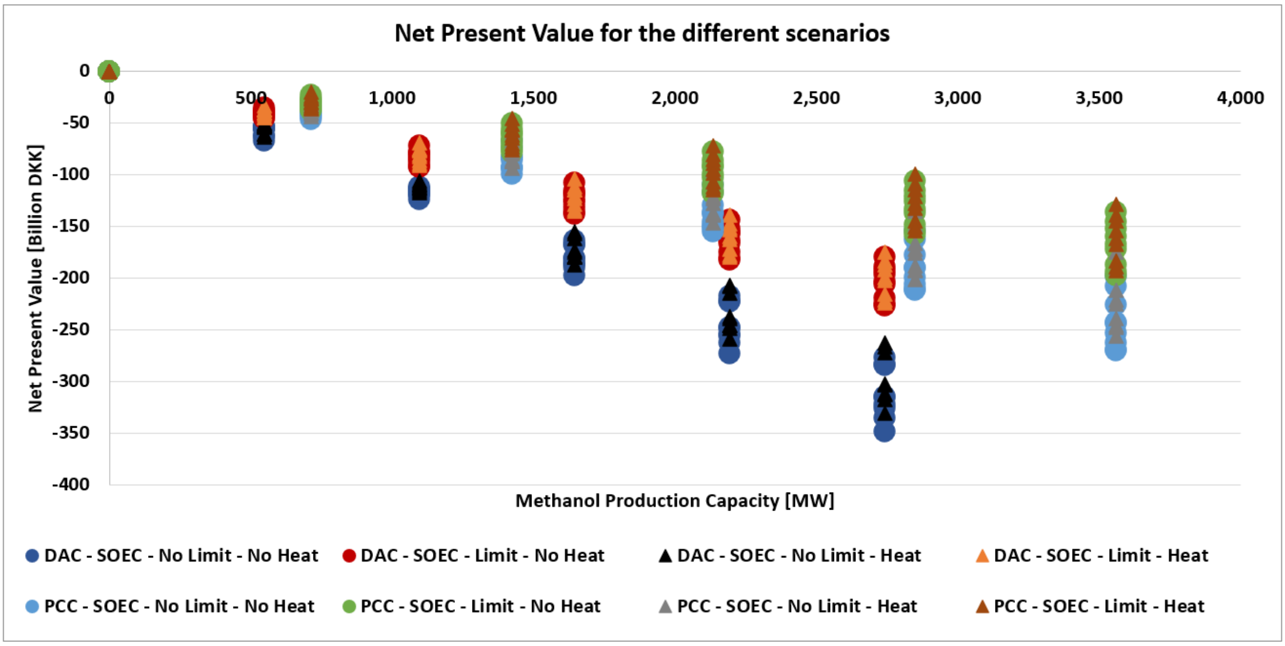

Figure 6 – Indicates the Net Present Value for the different scenarios, when they are impacted by different parameters from the sensitivity analysis, which creates the uncertainty for the different scenarios. Note, each color is a scenario, so the increase in capacity, and the range between the dots with the same color and capacity indicates their uncertainty. Higher is better. (Appendix B)

Figure 6 implies that all the scenario's NPVs are negative, which makes all the scenarios a bad investment, as they would yield a negative income. This seemingly implies that the utilizing PtX technologies is techno-economically unviable, when comparing it to the fossil fuel market.

But figure 6 also implies that there is a difference in the scenarios NPV. All the scenarios utilizing direct air carbon capture technologies, have a higher NPV than the scenarios using post combustion carbon capture technologies. All the scenarios selling excess heat has a higher NPV, in comparison to the counterpart scenario which does not sell excess heat.

Figure 6 also implies that the scenarios which only utilizes power from the wind turbines in the North Sea, has a higher NPV in comparison to the counterpart scenarios, which is allowed to purchase power from the Nord Pool spot market. This signifies that the operational strategy plays a crucial role in making the methanol plant techno-economically viable.

Figure 6 implies that as the capacity of the scenario's methanol plant increases, so does the range of the NPV. This means that as the scenario's capacity increases, so does the uncertainty of the scenarios NPV. This uncertainty signifies that if the given scenario is established, with a specific capacity, the NPV can be expected to be within the ranges given on figure 6. Although the development of the NPV, can only be expected, if no intervention or newer innovation occurs.

9.1.2 CO_2eq Emission Reduction

The CO_2eq emission reductions for the different scenarios, at different capacities, and the impact caused by different sensitivity parameters, can be seen on figure 7. The different scenarios are implied by the colors of the dots, as well as the capacity increase along the x-axis. The uncertainty associated with each scenario, investigated through the sensitivity analysis, is implied by the range of the same-colored dots at the same capacity. The CO_2eq emission reductions of these scenarios is given by the value on the y-axis. Each colored dot, representing the scenarios, is explained in the figure's legend.

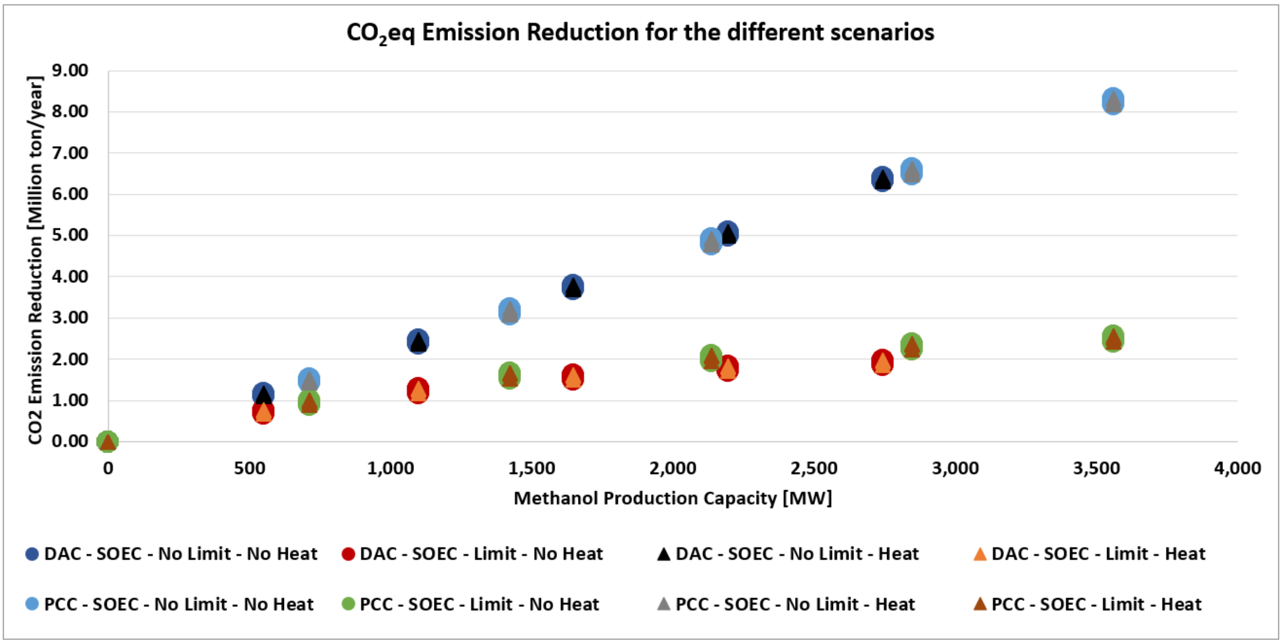

Figure 7 – Indicates the CO_2eq emission reductions for the different scenarios, when they are impacted by different parameters from the sensitivity analysis, which creates the uncertainty for the different scenarios. Note, each color is a scenario as well as the increase in capacity, and the range between the dots with the same color and capacity indicates their uncertainty. Higher is better. (Appendix B)

Figure 7 implies that when the scenarios capacity increases, so does the CO_2eq emission reduction. But there is a difference between the rate of increase between the scenarios, which is associated with the power source scenario. The emission reductions from the scenarios, which can utilize the electricity from the wind farms in the North Sea, the Nord Pool spot market, the special down and down regulation market, rises linearly to the increase of the capacity. But the emission reductions from the scenarios, which can only utilize power from the wind farms in the North Sea, the special down and down regulation market, decreases in magnitude as the capacity of the scenarios increases. The decrease in the scenario's emission reductions occurs because the scenarios are constrained, which means that as the capacity increases the availability of electricity in comparison to the capacity decreases, which means the methanol plants capacity becomes saturated in comparison to the amount of electricity available.

As it is expected that the use of the excess heat will replace other green technologies, there is no added CO_2eq emission reduction in the scenarios which sell excess heat, this indifference can be seen on figure 7. The emission reductions of the scenarios with sale of excess heat, is placed right on top of their counterpart scenario.

Figure 7 implies that the emission reductions caused by the different scenarios, reaches levels which are quite substantial in comparison to Denmark's national reduction goal. The scenarios with methanol production capabilities, reaches emission reduction levels which corresponds to between 1.02-10.98% of the total emissions in the base year of 1990. (Appendix B & Klimarådet, 2019)

Figure 7 implies that the emission reductions from the scenarios utilizing post-combustion carbon capture technologies, is higher than the scenarios utilizing direct air carbon capture technologies.

Figure 7 also implies that the uncertainty of the CO_2eq emissions for each scenario is really small. This is due to the fact that the methanol production for the individual scenarios, is only dependent on the weather patterns. The discount rate does not affect the emission reduction. This means that the historical data for the different year, which is used to model the sensitivity, is the only parameter which influences the uncertainty of the emission reduction for the individual scenarios.

9.1.3 The income per unit of methanol produced

The income per unit of methanol produced for the different scenarios, at different capacities, and the impact caused by different sensitivity parameters, can be seen on figure 8. The different scenarios are implied by the colors of the dots, as well as the capacity increase along the x-axis. The uncertainty associated with each scenario, investigated through the sensitivity analysis, is implied by the range of the same-colored dots at the same capacity. The income per unit of methanol produced in these scenarios is given by the value on the y-axis. Each colored dot, representing the scenarios, is explained in the figure's legend.

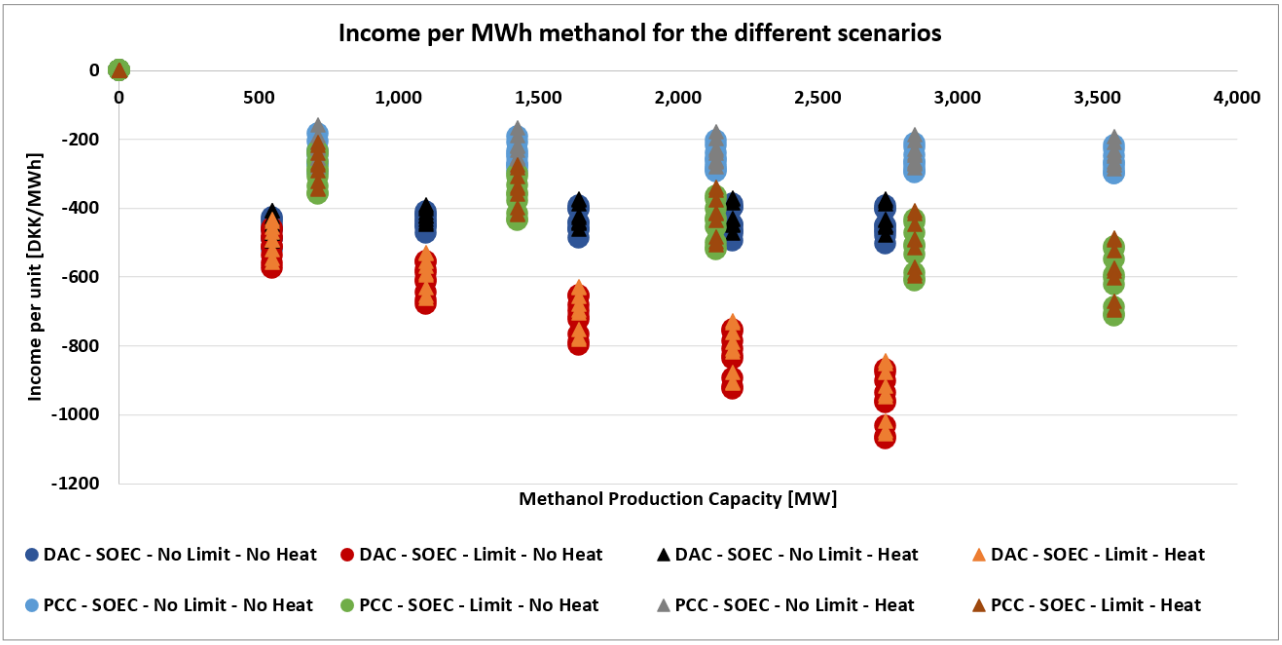

Figure 8 – Indicates the income per unit of methanol produced for the different scenarios, when they are impacted by different parameters from the sensitivity analysis, which creates the uncertainty for the different scenarios. Note, each color is a scenario as well as the increase in capacity, and the range between the dots with the same color and capacity indicates their uncertainty. Higher is better. (Appendix B)

Figure 8 implies that all the methanol produced will be sold at a loss for each unit, when comparing the methanol prices to methanol produced through fossil fuels. Furthermore, figure 8 also implies that the prices of the methanol produced ranges between -157.90 to -1070.44 [DKK/MWh] methanol. (Appendix B)

Figure 8 implies that the scenarios using direct air carbon capture (DAC), has a lower income for each unit of methanol produced, in comparison to the post-combustion scenarios (PCC).

Figure 8 implies that the income for each unit of methanol produced, steadily decreases for the scenarios which production is constrained by the wind farms in the North Sea, the special down and down regulation market. Whereas the scenarios which can also use electricity from the spot market, has a steady income per unit of methanol produced. The reason that the constrained scenarios income per unit of methanol steadily decreases, is because the production of methanol per capacity of the plant decreases, which is implied by figure 7. This means that the constrained scenarios have a high investment cost, increasing the NPV, without the plant actually producing any fuel to justify the high capacity.

Figure 8 implies that when the capacity of the unconstrained PCC scenarios increases, the income per unit of methanol gradually decreases. Figure 8 also implies that the opposite occurs for the unconstrained DAC scenarios, meaning that when the capacity increases for the unconstrained DAC scenarios, the income per unit of methanol produced increases. For both the PCC and DAC, these changes are very small, and may be attributed to the increased uncertainty.

Figure 8 implies that utilizing excess heat for all the scenarios, increases the income per unit of methanol produced. But not in a degree which makes a huge impact on the techno-economic viability, in comparison to changing the operational strategy or the technologies utilized. Note, that the cost of coupling the methanol plants to the district heating grid is not included. This could imply that utilizing excess heat might not be as beneficial for the techno-economic viability of the methanol plant, but could be beneficial from a societal perspective, as utilizing the excess heat might reduce the need for constructing a district heating unit.

Figure 8 implies that there is a large uncertainty associated with each scenarios income per unit of methanol produced, which might be caused by the fluctuating energy prices, as figure 7 implies the amount of methanol produced is not the cause of the uncertainty.

9.1.4 The CO_2eq emission reduction per NPV

The NPV for each CO_2eq emission reduction for the different scenarios, at different capacities, and the impact caused by different sensitivity parameters, can be seen on figure 9. The different scenarios are implied by the colors of the dots, as well as the capacity increase along the x-axis. The uncertainty associated with each scenario, investigated through the sensitivity analysis, is implied by the range of the same-colored dots at the same capacity. The NPV for each CO_2eq emission reduction in these scenarios is given by the value on the y-axis. Each colored dot, representing the scenarios, is explained in the figure's legend.

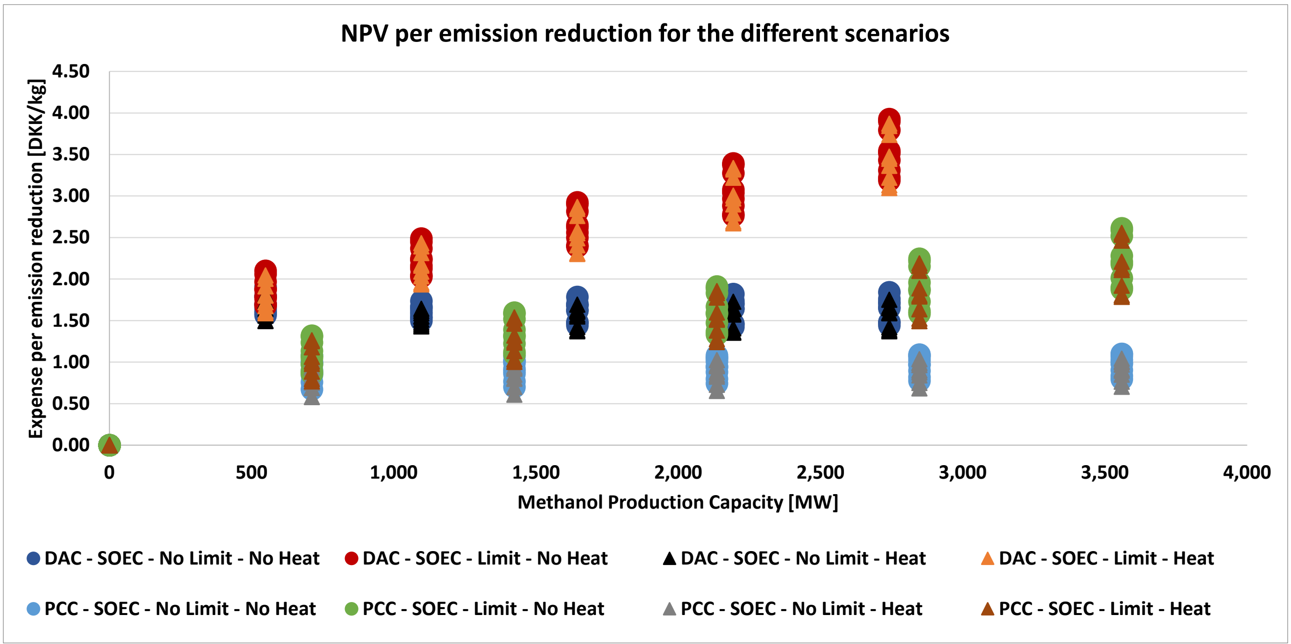

Figure 9 – Indicates the NPV for each CO_2eq emission reduction for the different scenarios, when they are impacted by different parameters from the sensitivity analysis, which creates the uncertainty for the different scenarios. Note, each color is a scenario as well as the increase in capacity, and the range between the dots with the same color and capacity indicates their uncertainty. Lower is better. (Appendix B)

As the NPV was negative, the net present value for each CO_2eq emission reductions will be defined as an expenditure per emission reduction.

Figure 9 implies that the expenditure per emission reduction, ranges between 0.58-3.93 [DKK/kg-CO_2eq], for the scenarios which actually produce methanol.

Figure 9 implies that the expenditure for each emission reduction, is lower for all the scenarios using post-combustion carbon capture (PCC) technologies, in comparison to the scenarios utilizing direct air carbon capture (DAC) technologies.

Figure 9 implies that the expenditure per emission reduction, is lower at lower methanol production capacities, and increases when the methanol production capacity increases, for the scenarios which utilizes PCC technologies. The figure also implies that unconstrained scenarios using PCC technologies, have a lower expenditure for each emission reduction, in comparison to the constrained scenarios using PCC technologies. Furthermore, figure 9 implies that the expenditure per emission reduction for the scenarios utilizing DAC technologies, which electricity source is constrained, steadily increases when the methanol production capacity increases. Whereas the expenditure per emission reduction decreases a little, for the DAC scenarios which electricity source is unconstrained.

Figure 9 implies that the sale of excess heat from the DAC scenarios, does not have a significant impact on the scale of the scenario's expenditure for each emission reduction. On the contrary figure 9 implies that the sale of heat from the PCC scenarios, has a significant impact on the expenditure for each emission reduction.

Figure 9 implies that when the capacity of all the scenarios methanol production capacity increases, the uncertainty of the emission reduction per expenditure increases.

9.1.5 The implications of the electricity uptake calculations

The calculated electricity consumption per MWh methanol produced, for the DAC-SOEC and PCC-SOEC scenario, can be seen on table 7. Furthermore, table 7 indicates the average electricity and methanol prices, of the different timeseries used in the model.

Table 7 - Indicates the avarage methanol and electricity price for the different years, as well as the electricity uptake of the DAC- and Post-Combustion SOEC methanol plant scenario (Appendix B)

Year	Methanol price [DKK/MWh]	Electricity price [DKK/MWh]	Plant	Electricity consumption per MWh methanol [MWh]
2017	497.19	511.79	SOEC and Direct Air CC	1.61
2018	544.13	616.32	SOEC and Post-Combustion CC	1.24
2019	444.7	575.39		

Table 7 implies that the price of fossil fuel-based methanol, is lower than the average electricity price for each year. This means that with a direct transfer coefficient of 1, the methanol produced through the electricity would be economically unviable. Table 7 shows that the unviability of electrofuels is further enhanced by the fact that methanol produced through electricity, will impose an energy loss in the conversion.

Table 7 therefore implies the reason as to why the NPV of all the scenarios become negative. The operational expenses exceed the operational income, which together with the investment cost, makes the negative NPV extremely high. This means that it is extremely hard to make the scenarios techno-economically viable when competing against methanol produced through fossil fuels.

9.2 MULTI CRITERIA EVALUATION OF THE MODEL RESULTS

This section will review the scenarios, through a multi criteria evaluation, which will be done by designating the best scenarios within each evaluation criterion, which has been established in section 8.7. The overall results of the scenarios can be found in section 9.1, but this section will go more into detail with what the results implies in regard to evaluating the techno-economic viability methanol plant and the CO_2eq emission reduction caused by the methanol plant, which has been investigated in this study.

The best scenarios have been found by comparing all the scenarios to each other, within each criterion, where the scenarios with the highest values achieve the highest ranks and vice versa. After this, all the scenarios achieve a score consisting of the average of their given ranks. Thereby, the scenario which generally performs the best within each criterion can be found.

As there are 40 different scenarios each with 9 variations resulting in 360 results, which has been evaluated through the multicriteria evaluation, the number of scenarios presented will be kept to a minimum. But all the evaluations of the different scenarios and their variations can be found in Appendix B. The scenario which performs the best within each criterion will be presented, as well as the scenario which generally performs the best. Furthermore, the scenarios surrounding the generally best performing scenario will be presented, to establish a reference point as to why the found scenarios outperforms the others. The scenarios which will be presented is the scenarios of interest.

The Net Present Values, CO_2eq emission reductions, the income per unit of methanol produced and the expenditure for each emission reduction, for each of the scenarios of interest, is presented on table 8. Furthermore, each of these scenarios ranks within the different criteria is also given on table 8. The values represent the top values of each scenario, which is deemed a suitable approach to choose the different scenarios, as their development follows the same trend, regardless of the uncertainty of the given scenario. This means the top values of the scenarios, will be used to implicate the best scenarios in regard to the multicriteria evaluation.

Table 8 - Indicates the top performing scenarios, within the different criterias specified in the multicriteria evaluation. Furthermore, the table indicates the performance of the scenarios surrounding the generally top performing scenario. Each of the values represent the top of each scenario. (Appendix B)

Top Scenarios	**Net Present Value**		**CO_2eq Emission Reduction**		**Income per unit of methanol**		**NPV per CO2eq Emission Reduction**		
	Value [Billion DKK]	**Rank**	**Value [Million ton/year]**	**Rank**	**Value [DKK/MWh]**	**Rank**	**Value [DKK/kg]**	**Rank**	**Average Rank**
PCC-SOEC 20% - Limit - Heat	-20.52	1	0.89	338	-209.45	17	0.77	17	93.25
PCC-SOEC 100% - No Limit - No Heat	-198.45	294	8.31	1	-216.91	20	0.8	19	83.5
PCC-SOEC 100% - No Limit - Heat	-175.4	257	8.31	1	-191.71	9	0.7	9	69.25
PCC-SOEC 20% - No Limit - Heat	-26.4	5	1.52	266	-157.9	1	0.58	1	68.25
PCC-SOEC 20% - No Limit - Heat	-26.4	5	1.52	266	-157.9	1	0.58	1	68.25
PCC-SOEC 40% - No Limit - Heat	-58.61	73	3.21	110	-165.73	2	0.61	2	46.75
Scenarios surrounding the generally top performing scenario									
PCC-SOEC 40% - Limit - No Heat	-56.52	71	1.68	235	-306.51	105	1.12	105	129
PCC-SOEC 40% - Limit - Heat	-45.95	54	1.53	260	-273.38	75	1	74	115.75
PCC-SOEC 40% - No Limit - No Heat	-67.52	86	3.21	109	-190.92	8	0.7	7	52.5
DAC-SOEC 40% - No Limit - Heat	-107.79	146	2.48	140	-395.5	139	1.45	138	140.75
DAC-SOEC 40% - Limit - No Heat	-78.58	103	1.29	289	-552.89	270	2.03	270	233
DAC-SOEC 40% - Limit - Heat	-75	95	1.29	290	-527.7	264	1.94	261	227.5
DAC-SOEC 40% - No Limit - No Heat	-114.66	160	2.48	139	-420.69	161	1.54	159	154.75

9.2.1 Criterion 1 - The Net Present Value

Through figure 6 it became apparent, that none of the methanol plants were techno-economically viable, when competing in the fossil fuel market. In that regard, it must be noted that the best option would be to not invest in any of the scenarios, if it is not possible to increase the price of the green methanol in comparison to the fossil-fuel based methanol. The scenario, which actually produces methanol, with the highest NPV will be chosen regardless of it being negative.

The scenario with the highest NPV is the PCC scenario which is dimensioned with an electricity uptake capacity of 20% in comparison to the nominated capacity of the wind farms in the North Sea. The scenario can sell its excess heat and is limited to only produce when it can receive power from the wind farms, the special down and down regulation market. On figure 6 the scenario can be identified through the PCC – SOEC – Limit – Heat dot ▲, which methanol production capacity is 711.85MW.

Section 9.1.5 attributes the high negative NPV's to the electricity- and methanol price. This means that the reason that the PCC-SOEC 20% - Limit – Heat scenario is ranked the highest in the NPV criteria, is that the scenario consumes a lot less electricity than the other scenarios, as a consequence lowering the losses associated with the scenario. Scenario consumes less electricity, because its efficiency is higher, and it can only consume power from the wind farms in the North Sea.

The drawback of this scenario is that it does not decrease the CO_2eq emissions as much as the other scenarios, as can be seen on the rank and color indication on table 8. Because the scenario does not utilize a lot of electricity from the Nord Pool spot market but acquires a lot of cheap electricity through the wind farms in the North Sea, the special down and down regulation market, the scenario's methanol unit price is quite cheap. Even with the low emission reduction, this scenario has a high emission reduction for each expense.

9.2.2 Criterion 2 – The CO_2eq emission reduction

Through figure 7, it became apparent that all the scenarios can significantly reduce the CO_2eq emissions, by displacing the amount of used fossil fuels.

The scenario with the highest CO_2eq emission reduction, is the PCC scenario which is dimensioned with an electricity uptake capacity of 100% in comparison to the nominated capacity of the wind farms in the North Sea. The scenarios electricity source is unconstrained, and it is both the scenarios which sells excess heat and does not, which has the highest emission reduction. On figure 7 the scenarios can be identified through the PCC – SOEC – No Limit – Heat and No Heat dots ▲ and ●, which methanol production capacity is 3559.27MW.

Both the PCC-SOEC 100% - No Limit – Heat and No Heat scenarios have an extremely high NPV, with the No Heat scenario being higher than the other. This high NPV means that the scenario is very unlikely to be established, as the scenario could impair Denmarks state budget, eventhough the scenarios would decrease the GHG emissions with 10.98% in comparison to the basis year of 1990. The scenarios have a high income per unit of methanol produced, as well as a high emission reduction per expenditure in comparison to the other scenarios.

9.2.3 Criterion 3 – The Income for each unit of methanol produced

Through figure 8, it became apparent that the income for each unit of methanol produced decreased for each scenario when the production capacity increased, with the exception of the unconstrained DAC – SOEC scenario.

The scenario with the highest income for each unit of methanol produced, is the PCC scenario which is dimensioned with an electricity uptake of 20% in comparison to the nominated capacity of the wind farms in the North Sea. The scenarios electricity source is unconstrained and the scenario sells excess heat. On figure 8 the scenario can be identified through the PCC – SOEC – No Limit – Heat dot ▲, which methanol production capacity is 711.85MW.

Table 8 indicates that the PCC-SOEC 20% - No Limit – Heat scenario has the fifth highest rank in its NPV in comparison to the other scenarios, which implies that the scenario is probable to establish, in comparison to the other scenarios. But it does not have a high emission reduction, which means the scenario might not be politically favorable. The scenario also has the highest income for each unit of methanol produced.

9.2.4 Criterion 4 – The CO_2eq emission reduction per NPV

Through figure 9, it became apparent that the expenditure for each scenario's CO_2eq emission reductions were lower at lower production capacities, and increased as the capacity increased. This occurred for all the scenarios, with the exception of the unconstrained DAC – SOEC scenarios, which decreased a little.

The scenario with the lowest expenditure for each associated emission reduction, is the PCC scenario which is dimensioned with an electricity uptake of 20% in comparison to the nominated capacity of the wind farms in the North Sea. The scenarios electricity source is unconstrained and the scenario sells excess heat. On figure 9 the scenario can be identified through the PCC – SOEC – No Limit – Heat dot ▲, which methanol production capacity is 711.85MW.

The scenario also scored the highest in the income for each unit of methanol produced.

9.2.5 The highest ranking scenario

The scenario which performs the best when weighing all the scenarios criterions against each other, is the PCC scenario which is dimensioned with an electricity uptake of 40% in comparison to the nominated capacity of the wind farms in the North Sea. The scenarios electricity source is unconstrained and the scenario sells excess heat. On figure 6, 7, 8 and 9 the scenario can be identified through the PCC – SOEC – No Limit – Heat dot ▲, which methanol production capacity is 1423.71MW.

The scenario, which is generally ranked the highest, has an NPV which might be politically more attractive, as a higher impact on the emission reduction is achieved. The scenario does not have the highest emission reduction, but it does provide a good amount of reduction in comparison to many of the other scenarios, which also have a great expense for each emission reduction. The scenario is ranked second in the expense for each reduction criterion and the income for each unit of methanol produced.

The high ranks of this scenario could be used as an argument for why it should be established, if there is a political willpower to reduce the CO_2eq emissions, even though the NPV is negative.

If it is not possible to establish the district heating, table 8 suggests that the PCC-SOEC 40% – No Limit – No Heat scenario ● might be the best substitute.

Furthermore, if there is not enough CO_2 available through Post-Combustion Carbon capture, table 8 indicates that the DAC-SOEC 40% - No Limit scenarios can be a great substitute to the suggested scenario. Or a smaller portion of the DAC-SOEC scenario could be established in conjunction with the highest-ranking scenario, if there is not enough CO_2 available through PCC.

9.3 Escaping a fossil fuel dependency

Through the theory of path dependency, it was predicted that escaping existing systems can be extremely economically costly, as a result creating a carbon lock-in. Through section 9.1 and 9.2, it became apparent that even with the optimal scenario, it will be costly to escape the existing system. This study therefore confirms the theory, that Denmark is locked in a carbon dependency, as the market has achieved a vendor lock-in. The vendor lock-in is achieved, as a price increase of 165.73-276.19DKK for each unit of methanol, depending on the optimal scenario's uncertainty, seems too expensive for the market to absorb without the companies purchasing the green methanol losing their competitive advantage.

But as suggested by the theory of path dependency, if a new system is established, this system could become the determining system dictating the normal prices for each unit of fuel. If the electrofuels technologies takes over the fossil fuel market, it can be expected that the large demand would drive competitive industries to innovate and optimize their setup, as a result lowering the prices. Furthermore, with a larger demand for electrofuels there would be a higher demand for large scale PtX plants, this could mean that components used in the PtX plants could be mass produced, as a result lowering the prices even further than indicated by the technologies given by the DEA. Furthermore, the increased electricity consumption from energy conversion units, can have a large cumulative impact on other energy producing units. This impact could be positive, as PtX allows more fluctuating energy sources to enter the market, as a result increasing the confidence in producing more fluctuating energy sources. Ultimately these cumulative effects could drive down the electricity prices, thereby making the operation of PtX plants more viable.

This hypothetical development could be great, but as the study implies, there is no economic benefit in investing in the establishment right now, which creates a stalemate for the development of the PtX technologies.

The theory institutional change suggests multiple ways to break the stalemate, by changing the regulatory, normative, and cultural cognitive institutions.

9.3.1 Regulatory institution

A way to break the vendor lock-in, which through the optimal scenario was established to be 165.73-276.19DKK extra for each equivalent amount of fuel, is through regulation. It must be noted, that for any regulation to be passed into law, there must be a political willpower to pass it. This means, that even though there is a political will power to support green initiatives, which through the problem analysis in section 5.1 was established to be the case for the current government, the green initiatives must still make sense in regard to the expenditure for each emission reduction and the laws must not infringe the rights of the citizens.

CO_2eq emission Tax:

One of the ways to make the establishment of the optimal scenario a possibility, is to impose a CO_2eq emission tax, which at least adds an expense to the fossil fuels equivalent to the 165.73-276.19DKK extra payment for the CO_2 neutral methanol. Although this approach could have some derivative effects, such as other industries, which have a harder time to transition, losing their competitiveness forcing them to move to other countries.

This CO_2eq emission tax could be equivalent to the amount of expenses associated with each emission reduction in the optimal scenario. Which would mean that the CO_2eq emission tax could be 0.61-1.01DKK for each emitted kg of CO_2. This tax would off-set the technoeconomic viability of the optimal scenario, making it reach cost-parity with methanol produced through fossil fuels.

Energy unit subsidies:

Another way to make the establishment of the optimal scenario a possibility, is to impose a subsidy on each unit of methanol produced through electricity. The benefits of subsidies are that they can be tailored to the specific subject and does not impact other sectors directly like a carbon emission tax. The subsidy could be directly equivalent to the loss associated with the production of each unit of methanol, meaning that the subsidy could be around 165.73-276.19DKK per MWh methanol produced through PtX-technologies. It should be noted that there should not be given any subsidies to PtX-technologies, in hours where the electricity is produced through other fuels, as it does not make sense to subsidize the production of fuels from other fuels as it incurs an energy loss.

9.3.2 Normative & Cultural cognitive institutions

Another way to break the vendor lock-in of 165.73-276.19DKK per MWh methanol, can be through a mixture of social pressure and volunteering. As mentioned in section 7.2 the social pressure can be created through industry agreements, where companies using high amounts of fossil fuels, become excluded from other companies' contracts, as they do not want their carbon footprint to be transferred to them. Furthermore, as mentioned in section 7.2, the consciousness of individuals within companies can make them want to purchase CO_2 neutral methanol, meaning they voluntarily absorb the extra cost associated with the CO_2 neutral fuel. But for the industry agreements to become valid or the creation of voluntary price absorption, the carbon footprint must become traceable. Therefore, it would be beneficial to create a certification scheme for carbon neutral fuels, which are derived through electricity. Furthermore, these carbon neutral fuels produced through electricity, would have to be tied to the certification scheme for green electricity.

If this traceability is created, the different companies and individuals might be more willing to pay the extra 165.73-276.19DKK for the methanol produced through electricity, thereby making the optimal scenario techno-economically viable.

10 DISCUSSION

In this chapter, the major uncertainties associated with the study will be discussed and put into perspective. The possible way to establish a PtX plant in the form of a methanol plant will be discussed. Lastly the attribution of the carbon emission reduction will be discussed.

10.1 UNCERTAINTIES AND THEIR IMPLICATIONS

One of the main uncertainties in this study, is that the methanol plant is expected to acquire all the special down and down regulation power volumes available, in each market. This expectation is uncertain, because it can be extremely hard for the methanol plant owners, to accurately predict the markets development in each hour. And in this study, this precise prediction would be needed, in order for the methanol plant to acquire all the down and special down regulation power volumes. As it was implied in section 9.1.5, that the electricity price is a determining factor for the techno-economic viability of the methanol plant, the Net Present Value (NPV) might increase in reality. The NPV might increase in reality, because a reduced use of the down and special down regulation market, could mean that larger quantities of power would have to be acquired at higher prices. Although, this approach does show the economic impact of the down and special down regulation markets have on the techno-economic viability of a methanol plant. Thereby the possible market advantages, which could be bestowed upon the methanol plant through regulations, has been enlightened. If such regulations were established, it could be disadvantageous for other energy producing units, such as heat pumps and electric boilers used in publicly owned heating companies. Such an approach could create a techno-institutional complex, where competing companies would object, as the approach could be seen to go against the liberalization of the electricity system. Furthermore, if wrong predictions are made, the methanol plant might lose out on potential production the following day, as they have missed the bidding opportunity in the other markets. This means that the methanol plant might be locked out of the market, due to gate closure, which means that the predictions will have to be really accurate.

Another of the main uncertainties in this study, is the price estimation of the methanol synthesis plant. This estimation is an uncertainty, because the estimation was created by subtracting the DAC – SOEC technologies from the methanol plant established by the DEA, which could create two possible uncertainties The first uncertainty is that the methanol synthesis plant investment cost might be too high, as the comparable technologies were quite new when the methanol plant the DEA uses as a reference was established, meaning that the initial investment cost of the DEA methanol plant, might be substantially higher because of the carbon capture and electrolyzer technologies. This could mean that the prices of the carbon capture and electrolyzer technologies used in the DEA methanol plant might be so high, that when the newer and possibly cheaper DAC- SOEC technologies are extracted from the DEA methanol plant, the investment cost of the methanol synthesis plant per unit methanol produced is too high. The opposite might also be true, that the price of the DAC – SOEC technologies are lower, in comparison to the methanol synthesis plant. This could mean that the NPV value of the scenarios either becomes too low or too high, which also impacts the emission reduction per expense and income per unit of methanol produced. This uncertainty could have been accounted for, by including an investment cost range in the sensitivity analysis.

The PCC SOEC 40% - No Limit – Heat scenario, might not be the most optimal scenario in reality, as it is unknown where the methanol plant might be placed. Because if the methanol plant is placed too far from any existing heating grid, it might be costly to establish district heating pipes between the plant and the district heating grid, thereby maybe outweighing the benefits of utilizing the excess heat of the scenario. It might also be too expensive to establish the methanol plant near an urban area, with a district heating grid, if new transmission lines have to be established between the methanol plant and the wind farms in the North Sea. The next step of this study could therefore be to discover the optimal location for the methanol plant, then establish whether or not the sale of excess heat can outweigh the cost of creating either forms of connections. If this is not the case, then this study suggests that the PCC SOEC 40% - No Limit – No Heat scenario might be more optimal.

One of the other major uncertainties in this study is the operational strategy, because in the unconstrained scenarios, the methanol plant receives power from the Nord Pool spot market. As there are many power sources available on the Nord Pool spot market, it is in this study unknown where the electricity originates. This means that the power source origin is the uncertainty. In this study the unconstrained scenario runs a continuous operation in the model, which means that some of the power received must originate from fuel consuming power plants or CHP's. The scenarios can therefore arguably be called counterproductive, as they will consume power produced through fuels, in order to produce other fuels. It would therefore be beneficial to investigate an operational strategy, which shuts down the methanol plant, if a part of the electricity is produced by the use of fuels.

Another crucial uncertainty is the omission of the oxygen produced as a biproduct to the methanol. Oxygen is a commodity which is sold to different businesses and is used in large quantities in the steel industry. It could be that the sale of oxygen increased the operational income of the methanol plant, as it would sell two products instead of one, which in the current scenarios is emitted into the atmosphere. The sale of oxygen could have been included in the techno-economic assessment and might have been beneficial for the techno economic viability of the methanol plant.

Another approach in the techno-economic assessment could have been to compare the methanol prices to diesel prices, then see whether omitting taxation on methanol, might have been a possible solution for the suggested methanol plant to reach cost parity with the fossil fuels.

10.2 ESTABLISHMENT OF THE METHANOL PLANT

When observing that the price for each kg of CO_2 emission reduction is 0.61-1.01DKK, it becomes apparent that there might be other solutions to decreasing the GHG emissions, which are cheaper than the suggested scenario. But in the case that there is no other choice but to establish a methanol plant, which can provide fuels to sectors which cannot be electrified without a large unknown breakthrough, small scale methanol plants might be more suitable. Because if small scale methanol plants are established, instead of creating methanol plants with gigantic capacities, the PtX industry might develop incrementally. This approach might allow the price to drop even further, maybe increasing the CO_2 emission reduction for each expense.

In section 9.3.1, it was explained that a carbon emission tax might be a great approach to increasing the technoeconomic viability of the methanol plant, but the approach might also create a techno-institutional complex (TIC), where all the different industries will lobby against the carbon tax. These companies might warn politicians against the tax proposal, under the pretense that they will have no other choice but to move their production facilities out of the country. In some cases, this might be true and in others it might not be, but the TIC will make it hard to differentiate between the cases. Furthermore, there could be huge complications with the quantification of the tax, as some might suggest it to be lower than the 0.61-1.01DKK for each emitted kg CO_2eq which is emphasized in this report. The TIC might be avoided by using subsidies, as the other industries will not be impacted, and the industries which will be associated with the PtX industries stands to gain more. Even though these subsidies might remove the TIC from the industries perspective, the citizens who pays the taxes towards the development of the PtX industry, might be more inclined to object as it from their perspective might seem like a waste of their money. Because in the end, the subsidies used to pay for the development of the PtX industry, will have to be taken from somewhere in the national budget or the taxes has to be increased somehow.

The TIC might be completely removed, if a combination of the different institutional changes is used in combination with each other.

There can be many different combinations of all the institutional change approaches, but one way to remove the TIC could be to split the expenses associated with the suggested methanol plant, into the three different institutional change approaches explained in section 9.3.1. This could be done by attributing the third of the cost to each of the approaches.

By attributing the third of the cost to each institutional approach would mean that a carbon emission tax could be between 0.2-0.34DKK for each emitted kg CO_2, consequently increasing the cost of using fossil fuels, making the PtX industry closer to reach cost parity.

By creating a subsidy which covers a third of the loss, associated with producing methanol from the optimal scenario, the subsidy would be between 55.24-92.06DKK for each MWh of methanol created by the methanol plant.

It can then be assumed that through certification schemes, the remaining cost of 55.24-92.06DKK for each MWh might be absorbed voluntarily by consumers, without the consumers being impacted by a vendor lock-in.

The TIC might be removed through this approach, as private companies, the government, and the consumers are pitching in, making it more possible that every party will be contempt.

Furthermore, if the societal costs associated with Denmark importing fossil fuels is considered, the use of higher subsidies for PtX technologies might seem more positive, as the Danish citizens might gain more employment probably increasing their prosperity.

10.2.1 Creation of a CO_2 neutral fuel lock-in

Through the suggested institutional changes, a PtX industry might be created. If the optimal scenario is established in Denmark, the whole PtX industry might be encouraged to develop even further, with the reward of being more competitive against other PtX technologies. This could mean that the small capacity of PtX technologies in Denmark is incrementally developed, where the electrofuels capacities starts small, but then expands continuously. It could be that as the industry develops, new supply chain companies will be developed, potentially lowering the prices for PtX-technologies even further. As a result of Denmark's policies, the PtX industry might become price competitive with the fossil fuels, which means that other countries' companies might adopt the technologies. These countries' businesses might cooperate with the Danish businesses, meaning that the Danish companies will grow even further. It could be that the development of the Danish PtX industry might pay back the all the subsidies which were given to the development of the industry. A situation which might be similar to the development of the wind turbine industry.

It could be that if the PtX industry completely replaces the need for fossil fuels, in sectors were fuels are essential, the supply chains of the fossil fuel industry will diminish. If the supply chains of the fossil fuel industry are diminished, it could mean that it would be too costly to revert back to using fossil fuels, in comparison to electrofuels. As a result, a new vendor lock-in is created, which is a CO_2 neutral fuel lock-in, which at current times would seem nonsensical to try to escape.

11 CONCLUSION

Through the problem analysis it was discovered that Denmark strives to reduce it GHG emissions by 70%, in comparison to the 1990 base year. Furthermore, it was discovered that there are multiple sectors, which cannot reduce their GHG emissions by being electrified. It was discovered that sectors which cannot be electrified, might replace their fossil fuel consumption with carbon emission neutral fuels, which can be produced through PtX technologies.

The problem analysis created a need to investigate the techno-economic viability of the PtX technologies, as well as these technologies possible GHG emission reduction.

It was then theorized that a carbon lock-in might occur, due to the price associated with changing existing institutions. In conjunction with this theoretical problem, a theoretical way to escape the lock-in was found through institutional change theory.

In this study, it was found suitable to establish different scenarios to investigate the techno-economic viability of the PtX technologies, as well as their GHG emission reduction. A sensitivity analysis was used to discover these scenarios uncertainties. These scenarios were then inserted into a model, which simulated the scenarios proposed PtX-plants, in conjunction with the wind farms in the North Sea.

Through the analysis, it was discovered that all the scenarios were techno economically unviable, even though the scenarios could significantly reduce the GHG emissions from Denmark. The techno economic assessment showed that all the scenarios would lose between 157.90 to 1070.44 DKK for each MWh of methanol produced. The assessment of the GHG emission reductions, showed that the scenarios suggested methanol plants might reduce Denmark's annual emissions with between 0.69-8.31 million tons of CO_2eq, equivalent to between 1.02-10.98% of the emissions in the base year.

The multi criteria evaluation suggested that the PCC SOEC 40% - No Limit – Heat scenario was the most optimal scenario, in regard to its techno-economic viability and its GHG emission reduction, but through the discussion it was debated that there might be some uncovered aspects of this scenario. In that regard, it was suggested that the PCC SOEC 40% - No Limit – No Heat scenario might be the most optimal scenario.

The analysis showed that the hypothesis of a carbon lock-in being true in regard to electrofuels, but the analysis also found the quantities of the potential carbon tax, the subsidies, and the voluntary price absorption the consumers can choose. Lastly, it was discussed that to avoid a techno-institutional complex, a mix of the different institutional change approaches could be used. Each of the approaches could be responsible for one third of the methanol plants income for each unit of methanol produced, enabling the methanol plant to reach cost parity with fossil fuels, thereby making the optimal methanol plant techno-economically viable. These prices would be a 200-340DKK tax for each emitted ton of CO_2eq, a subsidy of 55.24-92.06DKK for each MWh of methanol created by the methanol plant and a certification scheme which can be expected to make the consumers voluntarily absorb the remaining 55.24-92.06DKK for each MWh methanol. Although these prices were only applicable for the optimal scenario.

12 PERSPECTIVATION

By the end of the study, it was found that there were multiple ways to improve the projects results, by including more approaches in the investigation. These are:

1. Establishing a scenario which contains a photovoltaic production capacity on top of the wind turbine production capacity.
2. Establishing a scenario which contains a source of hydro power production capacity on top of the wind turbine production capacity.
3. Establishing a scenario where the hydrogen and CO_2 can be stored, to investigate the possibility of utilizing PtX technologies better in conjunction with fluctuating electricity sources.
4. Establishing a scenario where the heat input for the CC technologies is generated through a heat pump.
5. Establishing a scenario with DK1's wind turbines power generation capacity.
6. Adding the produced oxygen as a product, which can also be sold in the model similarly to the methanol.
7. Creation of better operational strategies to ensure the PtX plant does not produce when CHP's or PP's are producing.
8. Including calculations of societal costs, associated with Danish fuel production vs. import of fossil fuels.
9. Establishing a scenario with reduced amount of awarded power volumes obtained through the down and special down regulation market.

13 APPENDIX A – MAIL CORRESPONDANCE

Hej

Hermed sender jeg den månedlige statistik over rådighedsbetalingen for reserver i Øst- og Vestdanmark samt statistik over omfanget af specialregulering.

Manuelle reserver (mFRR)

Betalingen for opreguleringsreserver i Vestdanmark i januar måned som helhed endte på 48.595 kr/MW, hvilket svarer til en gennemsnitspris på 65 kr/MW pr. time set over hele måneden. Dermed fortsætter prisen for manuelle reserver på samme rekordhøje niveau som i december 2020, og det er kendetegnende, at der er meget stærk døgnvariation i priserne – altså langt højere priser for mFRR kapacitet om dagen end om natten.

I Østdanmark, hvor der nu også permanent bliver indkøbt opreguleringsreserver via daglige auktioner, blev gennemsnitsprisen 96 kr/MW pr. time svarende til et samlet provenu for 1 MW på 71.705 kr i januar måned som helhed. I modsætning til Vestdanmark, hvor der er meget stærk døgnvariation i priserne, er priserne i Østdanmark ensartede hen over døgnet og faktisk har prisen været konstant 60 kr/MW i alle timer igennem sidste halvdel af januar måned.

Foruden dagsauktioner i Østdanmark, indkøbes en del af de manuelle reserver via månedlige udbud. Månedsauktionen for januar 2021 medførte et køb på 329 MW til en pris af 32.735 kr/MW, hvilket svarer til 44 kr/MW pr. time. Månedsauktionen for februar 2021 har også været afholdt, og den resulterede i et køb på 358 MW til en pris af 32.690 kr/MW, hvilket svarer til 49 kr/MW pr. time.

Sekundære reserver (aFRR)

Siden 1. januar 2020 har Energinet indkøbt af aFRR reserver hos vestdanske aktører. Indkøbet sker i form af et månedsudbud. Den vægtede gennemsnitspris for 100 MW aFRR i februar måned 2021 er opgjort til 229 kr/MW/time svarende til en samlet udgift for måneden på 153.888 kr. pr. MW eller godt 15 mio.kr. i alt for 100 MW aFRR.

Frekvensstyrede reserver (FCR)

Indkøbet af FCR i Vestdanmark blev lavet om med virkning fra 19. januar 2021. Frem til dette tidspunkt blev FCR op- og nedregulering købt hver for sig på et isoleret, dansk marked. Fra og med 19. januar er FCR blevet købt som en symmetrisk ydelse på et nordeuropæisk marked, dog med den finurlighed, at 6 MW ud af det samlede behov på 20 MW skal være placeret i Vestdanmark. Hvis man kun ser på den symmetriske ydelse – dvs. sum af op- og nedregulering - så var betalingen for 1 MW de første 18 dage 235 kr/MW pr. time i gennemsnit, mens prisen faldt til 50 kr/MW pr. time efter overgangen til det nye marked i de sidste 13 dage af måneden.

Det kan videre oplyses, at mængden af accepterede bud fra vestdanske aktører i det nordeuropæiske marked har ligget mellem 6 MW (som er minimumskravet) og 26 MW (som er øvre maksimum) med et gennemsnit over de 13 dage på 12 MW pr. time. I en tredjedel af timerne har den danske lokalpris ligget over fællesprisen i det sammenhængende område.

I Østdanmark indkøbes aktuelt to frekvensprodukter, FCR-N & FCR-D, på et fælles svensk-østdansk dagsmarked. Priserne for disse to produkter er aktuelt stærkt på vej opad bl.a. som følge af kulde og høje spotpriser i Sverige. Prisen for FCR-N voksede med 50% i januar og hedder nu 153.000 kr/MW for måneden som helhed (~ 205 kr/MW/h). Prisen for FCR-D blev fordoblet forhold til december og ligger nu på 201.000 kr/MW (~ 270 kr/MW pr. time). FCR-D er altså igen blevet væsentlig dyrere end FCR-N, og ingen af de to produktpriser udviser væsentlig variation hen over døgnet.

Specialregulering

Specialreguleringsomfanget i januar måned 2021 endte på 333.500 MWh, hvilket er på niveau med niveauet i december 2020. Der har stort set udelukkende været tale om nedregulering af hensyn til flaskehalse i Tyskland. Ud af den samlede mængde nedregulering, har vestdanske aktører leveret 317.000 MWh og østdanske aktører 16.500 MWh.

I henhold til aftalen med Forsyningstilsynet er nedenfor alene vist den samlede mængde specialregulering og en gennemsnitspris som det tog sig ud for tre måneder siden - dvs. mængder og gennemsnitspriser til og med oktober 2020.

Leveret af danske aktører	jan-20	feb-20	mar-20	apr-20	maj-20	jun-20	jul-20	aug-20	sep-20	okt-20
GWh nedregulering	462	492	306	288	199	65	160	62	80	190
Gns.pris (kr/MWh)	-117	-180	-169	-196	-164	-238	-216	-202	-153	-153

En negativ pris for nedregulering betyder, at aktøren modtager penge for af skrue produktionen ned/øge elforbruget. I oktober 2020 leverede danske aktører i alt 190 GWh nedregulering til en gennemsnitspris på -153 kr/MWh – dvs. nedregulering i oktober måned har tilsammen givet danske aktører et provenu på ca. 29 mio. kr.

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