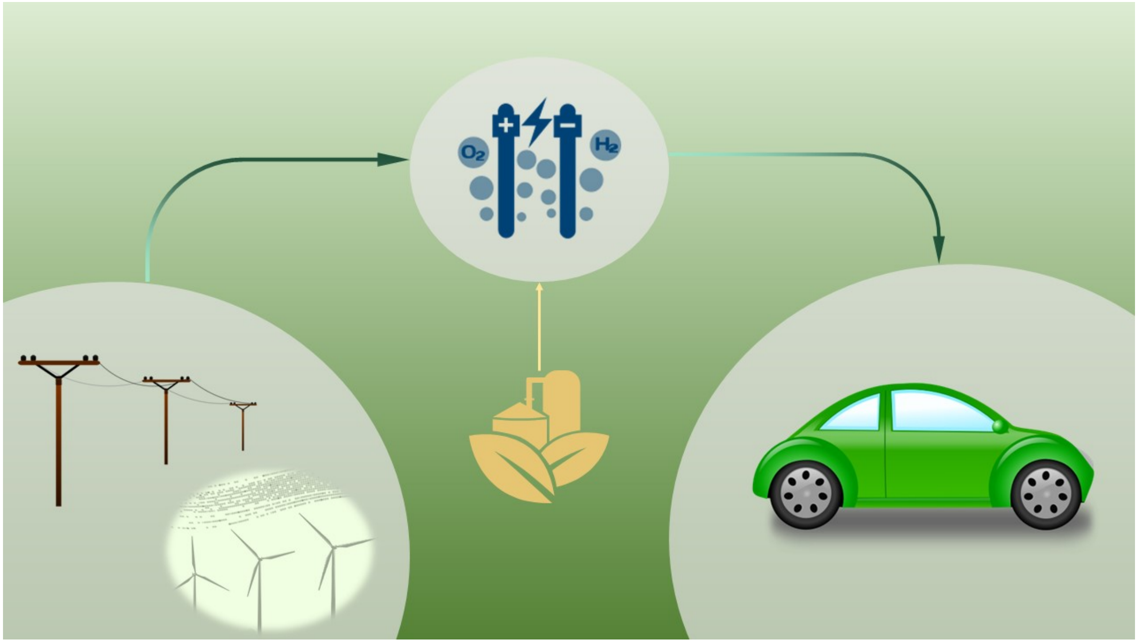
Aalborg University
Sustainable Energy Planning and Management



Socioeconomic Value Implementation For Power-to-X in Transportation

Authors:
Aksel Wedel Bang Jensen
Bruno Stefano Bez
Tore Bach Nielsen

Supervisor:
Peter Sorknæs

June 2020

4^{th} **semester at**
Faculty of Engineering and Science
Sustainable Energy Planning and Management
Rendsburggade 14
9000 Aalborg
https://www.en.engineering.aau.dk/

Title:
Socioeconomic Value Implementation For Power-to-X in Transportation

Project:
Master's thesis

4^{th} semester at
Sustainable Energy
Planning and Management

Project period:
February 2020 - June 2020

Project group:
Aksel Wedel Bang Jensen
Bruno Stefano Bez
Tore Bach Nielsen

Supervisior:
Peter Sorknæs

Pages (excl. appendices: 117)
Pages (incl. appendices: 131)
Appendices: 4
Finished: 04-06-2020

Synopsis:

The master's thesis investigates pathways of implementing a power-to-x (PtX) solution in the transportation sector by applying socioeconomic value. To do this the institutional framework has been investigated and a stakeholder analysis has been conducted to investigate the influence and power of interested parties. From some of the interviews conducted for the stakeholder analysis, it was found that most of the interested parties viewed power-to-methanol as having the highest potential in the near future for the transportation sector. An energy system analysis has been conducted to model the socioeconomic feasibility of different power-to-methanol solutions.
From this analysis, one type of power-to-methanol solution was picked and different parameters were changed to see the sensitivity of the plant. This sensitivity analysis additionally showed which inputs were able to create a positive NPV for the plant if changed.
The analysis showed that in the current framework it is not feasible to make a PtX plant. One of the more important aspects of valuing the societal value is the climate costs of greenhouse gas (GHG) emissions, which was seen to have a large effect on the NPV of the plant. Due to this, this thesis suggests that the actual value of GHG emissions should be determined and that this revenue should be provided for avoiding GHG emissions through alternatives to fossil fuels.

Resumé

Sustainability is becoming an embedded part of the different energy sectors, and while some of these sectors are making fast progress towards sustainability, the transportation sector is lacking. One of the solutions that can increase the sustainability of the transportation sector is producing renewable electrofuels via electrolysis and chemical synthesis in a process overall defined as Power-to-X (PtX). The process is energy-dense and is currently not considered to be competitive to its fossil fuel counterparts.

This competitiveness is mainly considered from a business economics point of view, but business economics does not account for the societal gains that the new production and use of electrofuels would enable. The feasibility study theory developed by Hvelplund & Lund (Hvelplund & Lund 1998) suggests that additionally to doing a business economic analysis, the societal gains should also be considered via a socioeconomic analysis when considering the feasibility of a system. Based on this theory, this report investigates the socioeconomics of small scale transition from gasoline to power-to-methanol usage and production and outlines a pathway to implementing the societal gains in a Danish context.

This investigation is conducted through both a stakeholder and energy system analysis. The stakeholder analysis outlines and maps out various stakeholders according to their influence and power towards the development of PtX in Denmark. The energy system analysis investigates the socioeconomic gains of building a 10 MW power-to-methanol. The emphasis in this report is that the fuel produced should be able to uphold a certain standard of sustainability, why the requirements used for defining the sustainability of the produced fuels were that used for biofuels. The stakeholder analysis concluded that the main power lies with a group of stakeholder defined as the *Regulators*. This mainly contains the central administration of Denmark, meaning the Danish Government, the Ministry of Energy, Utilisation and Climate. These do however have a low-risk approach due to the low technology readiness level of PtX.

The energy system analysis takes a socioeconomic approach and investigates four different scenarios for conducting and using methanol from electrolysis and found that none of the tested scenarios had a positive net present value (NPV), indicating no socioeconomic feasibility under the given parameters of the analysis. Furthermore, it was found that the most feasible method would be to implement a renewable electricity source directly connected to the plant. This type of plant was then tested in a sensitivity analysis, where it was found that the NPV and feasibility of the plant were highly dependent on the used price for CO_2 avoidance, which varies depending on which source is used, and how you value it. This report, therefore, concludes that a pathway to applying the socioeconomic value to PtX would be first to determine a suitable value for avoiding CO_2 emissions and secondly to add this value through tender schemes aimed at promoting the sustainable transition in the transportation sector.

Preface

This rapport is the master's thesis conducted at the 4^{th} semester in the master program of *Sustainable Energy Planning and Management* at the Department of Planning at Aalborg University. The master thesis has been carried through in the first semester period of 2020 from the 3^{rd} of February to the 4^{th} of June.

Harvard style referencing method is used in this report, which present the sources in the form (Name, year) throughout the entire report. The name refers to the last name(s) of the author and the year of publication. The reference is be placed in the text which uses the information provided by it. If more than one source is written by the the same author they are distinguished by using a letter after the year of publication. The references refer back to the *Bibliography* at the end of the report where a comprehensive reference list presents the name of the author, published year, the full title of the article, document, book or website, and if possible a hyperlink to a website. The note on when the source is assessed refer to the period of time when the source was either downloaded or observed for the first time. All tables and figures are labelled after the given chapter or section in which they are presented. If no reference is found, it should be assumed that the figure or table is made by the research group.

Numbers in this report are separated with spacing in between their thousand separators and a punctuation mark is used as a decimal separator.

The project group would like to give thanks to Ida Auken, Jacob H. Zeuthen, Jan Tjeerd Boom, Joahnnes Peschko, Mads Friis Jensen, Morten Egestrand and Morten Stryg for taking their time to line up for interviews.

A special thanks go out to Peter Sorknæs for his guidance and counselling throughout this Master's thesis project.

Reading guide

This report is divided into chapters which are further divided into section and subsection. These are marked by numbers, so the first subsection of the fourth section of the fourth chapter is named 4.4.1. Some subsections are further divided into various sections, which is indicated by a headline in **Bold** text. Tables and figures are named after which chapter they appear in, and in what order they appear, so the first Table in chapter four is named Table 4.1. The same applies to equations, but the equation is only noted by a number, so equation one in chapter four is called 4.1.

A number of appendices are added after the reference list. Instead of being named by numbers, these are named by letters like-so, A, B, C .. and so on. An overall structure of the report without the appendices can be observed in Figure 1.

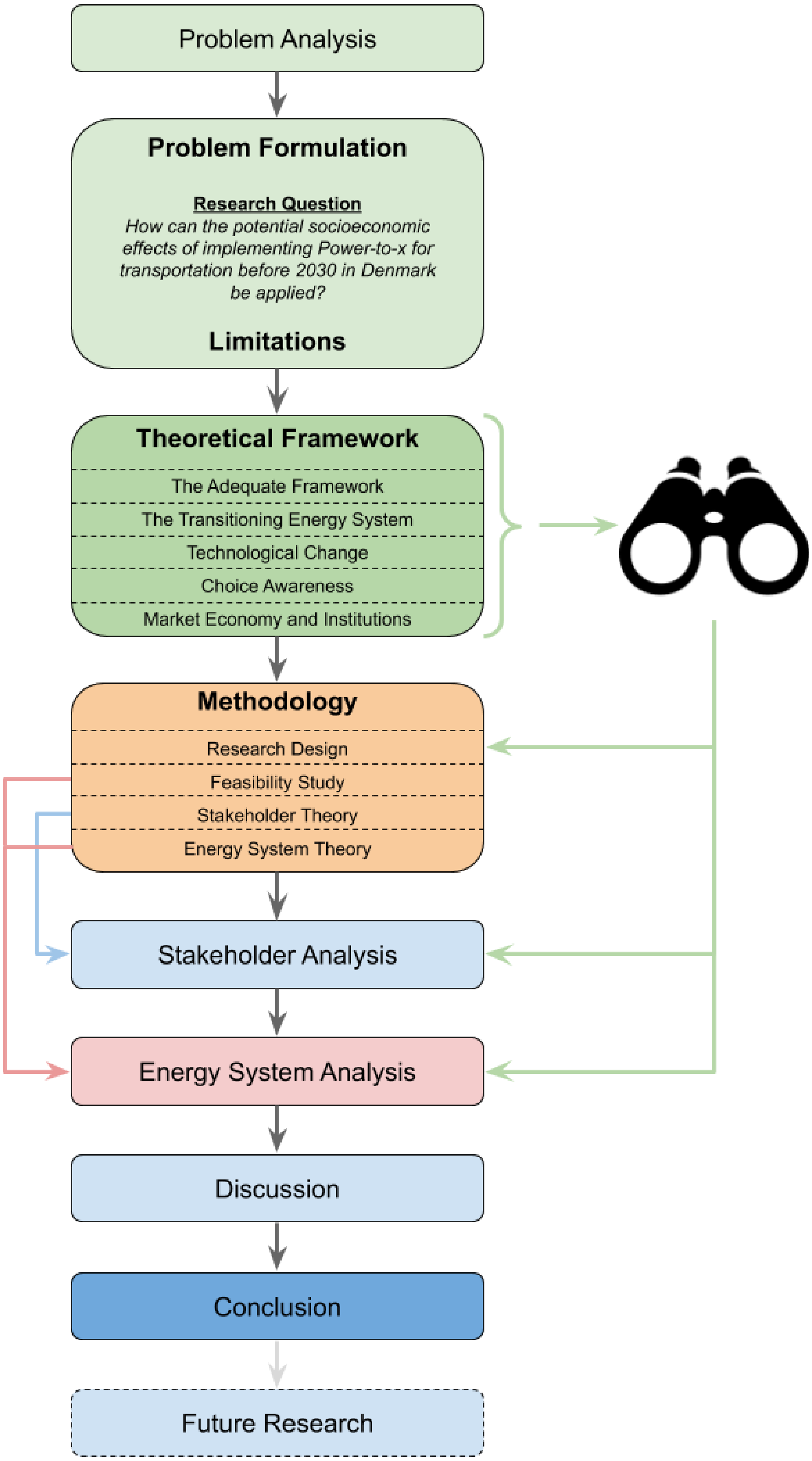


Figure 1: Report Structure

List of Abbreviations

- CCS Carbon Capture Storage
- CCU Carbon Capture Utilisation
- CFSR, Climate Forecast System Reanalysis
- CHP, Combined Heat and Power Plant
- DEA, Danish Energy Agency
- EU, European union
- EUDP, Energiteknologisk Udviklings- og Demonstrationsprogram
- EV, Electric vehicle
- FCH JU, Fuel Cells and Hydrogen Joint Undertaking
- FTE (full-time employment)
- GHG, greenhouse gas
- GO, Guarantees or Origin
- IDA, Danish Society of Engineers
- NTP (Normal Temperature and Pressure)
- PEM, Proton Exchange Membrane
- PP, Power Plant
- PtX, Power-to-x
- RE, Renewable Energy
- RED II, Renewable Energy Directive II
- RES Renewable Energy Source
- SOEC, Solid Oxide Electrolyser Cell
- TRL, Technology readiness level
- UN, united nations

Table of Contents

Problem Analysis 1

Sustainability has become an embedded part of the worldwide discourse and is an important aspect of development in the 21^{st} century. This also affects the development of energy systems where the fuel inputs are changing from fossil fuels towards renewable energy sources (RES) which are to be integrated and utilised in every sector of the energy system. New technologies for production, integration, and utilisation of RES are therefore emerging and trying to contribute towards the overall decarbonising of the energy system.

Sustainable development can nevertheless be comprehended differently and there are multiple definitions for when something is to be considered sustainable. A broad an international accepted definition of the term sustainable originates from the report *Our Common Future* released in 1987 by the United Nations (UN):

> *Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*
> (United Nations 1987, Page. 4)

This report furthermore defines sustainability to be considered by the three pillars of environmental protection, economic growth, and social equality (United Nations 1987). The understanding of sustainable development can be illustrated as in Figure 1.1 by Kørnov (Kørnov 2007), which shows how sustainability accommodates the environmental, economic and social pillars.

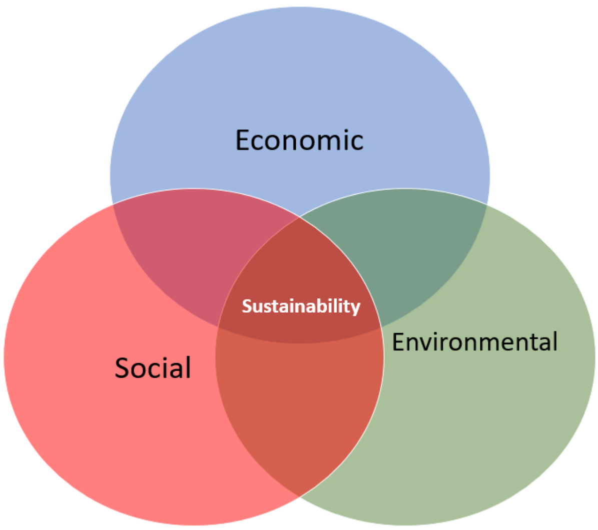


Figure 1.1: Own illustration of the three dimensions of sustainability (Kørnov 2007).

Understanding that sustainable development consists of these three pillars, where all are to be considered providing a more holistic view on development in general. Development therefore also needs to consider not only to be economically sustainable but also socially and environmentally sustainable. This understanding of sustainability has influenced the current energy visions and strategies which are creating the path towards a cleaner energy future.

1.1 Energy Visions & Strategies

This focus on sustainability became a global movement when the UNs World Commission on Environment and Development released the aforementioned report *Our Common Future*. As a result of this report and the increased focus on sustainable development, the UN conference on Environment and Development was established and held the first time in 1992 which resulted in the development of *Agdenda 21* (United Nations 1992*a*) and the United Nations Framework Convention on Climate Change (United Nations 1992*b*). However, these conventions had no binding requirements but resulted in the annual Conferences Of the Parties (COP) assemblies which in 1998 lead to the Kyoto protocol where state parties committed to reducing greenhouse gas emissions (United Nations 1998). In 2015 the UN released the Sustainable Development Goals (SDG) agenda with actions for people, planet and prosperity (United Nations 2015*b*) and later the same year at the COP-21 in Paris the *Paris Agreement* became the first global, comprehensive and legally binding climate agreement which sets out a global framework to limit global warming to well below 2°C and pursuing efforts to limit it to 1.5°C. (United Nations 2015*a*). All of these latter mentioned global agreements have changed today's approach towards development, which also encourages the energy sector to become more sustainable. Present regulations and laws in different areas such as climate or transport are therefore substantially impacted by these strategies which as a consequence also impacts the future regulatory framework.

This change in paradigm has been embedded at various levels and especially at the supranational level in the European Union (EU) where the current energy visions and strategies aim to utilise the goals from the Paris Agreement. The EU member nations are therefore required to develop national strategies and visions which align with the overarching EU strategies and visions to meet their commitments under the Paris Agreement and the EU objectives.

To ensure compliance and enforcement the EU has developed short term goals and actions for both 2020 and 2030 (European Commission 2010, 2014*b*) as listed in table 1.1, which aim to qualify the long term strategy for the EU to be climate-neutral (European Commission 2018). To enhance this the European Energy Union was established to ensure consistency in all policy areas and under the strategy to provide accessible, affordable, secure, competitive, and sustainable energy for all Europeans (European Commission 2015). As part of the Energy Union, the *Clean Energy For All Europeans* package was adopted to update the laws and legislation's in the energy sector to further accelerate the clean energy transition and contribute towards the EU's long term strategy and visions. The package aims to balance the power between the different layers of decision-makers in addition to enhancing synergies and efficiency across the borders.

Despite these transnational measures the package still allows each member state to individually design their energy system to reach national energy and climate targets within the EU context. (European Commission 2011) The latest strategy which is affecting the EU energy and climate sector is *The European Green Deal* which is a new growth strategy aiming to create a sustainable and inclusive transition towards a climate-neutral Europe (European Commission 2019*b*). The European Green Deal revises current plans, strategies, directives, and legislation's in 2020 and 2021 and suggests changes to enable a just and fair sustainable transition (European Commission 2019*a*). The current goals for the entire EU towards 2030 can be observed in table 1.1.

	GHG Emissions	**Renewable Energy**	**Energy Efficiency**	**Inter-connection**	**Climate in EU-funded programmes**	CO_2 **From:**
2020	-20%	20%	20%	10%	20% (2014-2020)	
2030	$\leq$ -40%	$\geq$ 32%	$\geq$ 32.5%	15%	25% (2021-2030)	Cars -37.5% Vans -31% Lorries -30%

Table 1.1: The 2030 climate and energy framework goals for the entire European Union. (European Commission 2019*c*)

The goals presented in Table 1.1 are not generic for every member state but apply to the European Union as a whole. The strategic dimensions behind these goals are imposed on all member states but the specific goals sates are negotiated between each state and the EU. This ensures that the EU reach the common goals outlined in table 1.1 and that each member state contributes a suitable amount accounting for their specific situation.

1.2 The Danish Context

Denmark and subsequently the Danish energy system is affected by the overall EU's energy and climate targets which are enforced in the mandatory EU strategy *Integrated National Energy and Climate Plan* (NECP) for the period 2021 to 2030 (Danish Ministry of Climate, Energy and Utilities 2019). The fundamental national political agreement behind this plan was reached in 2018 where all parties endorsed an *Energy Agreement* which aims to enhance sustainable development with focus on renewable energy (RE), energy efficiency improvements, research and development, and energy regulation (Regeringen 2018). Moreover, an agreement on a Climate Law was reached in 2019 which commits Denmark to take leadership on a global level in the sustainable transition and to cut national CO_2 emissions by 70% by 2030 (Regeringen 2019). These Danish commitments on reductions align with the overall global agreements at both the UN and EU levels and are even reaching further than the overall EU goals as presented in Figure 1.1. The ample Danish commitments concerning the common EU goals are shown in table 1.2 where the current Danish agreements and their commitments and goals are presented.

Agreement	Concerning	Commitment/Goal
Energy Agreement 2018	Denmark overall GHG emissions Share of RE	Net zero-emission society by 2050 No coal usage in electricity production after 2030 55% of RE of total energy consumption by 2030
EU: Effort Sharing Decision	GHG emissions Share of RE	39% reduction of emissions in the non-quota sector 7% of RE in the transportation sector by 2030
EU, Directive change	Energy efficiency	0.8% decrease each year in final energy consumption
Climate Law 2019	GHG emissions	70% reduction of GHG emissions in 2030. Climate-neutral by 2050
Danish NECP 2019 National EU 2030 goals	GHG emissions Share of RE	70% reduction of GHG emissions 55% RE in total energy consumption by 2030. $>$ 100% of electricity from RE by 2030 90% District Heating from RE

Table 1.2: Overview of the current Danish agreements in the energy and climate sector (Danish Ministry of Climate, Energy and Utilities 2019, Klimarådet 2019, Regeringen 2011, 2018, 2019)

The Danish commitments presented in Figure 1.2 are guiding the Danish society towards a more sustainable future and the common EU goals. As outlined, the Danish development is more ambitious in some areas than the common EU targets towards 2030. These commitments are according to the Danish Climate Council reachable but more actions are required to reach some of the targets e.g. the GHG emissions, RE amount in the transportation sector, and energy efficiency targets are to be reached (Klimarådet 2019). The Danish contribution towards the common EU goals can be observed in Figure 1.2 which shows that Denmark is close to reaching the common 2030 EU goals.

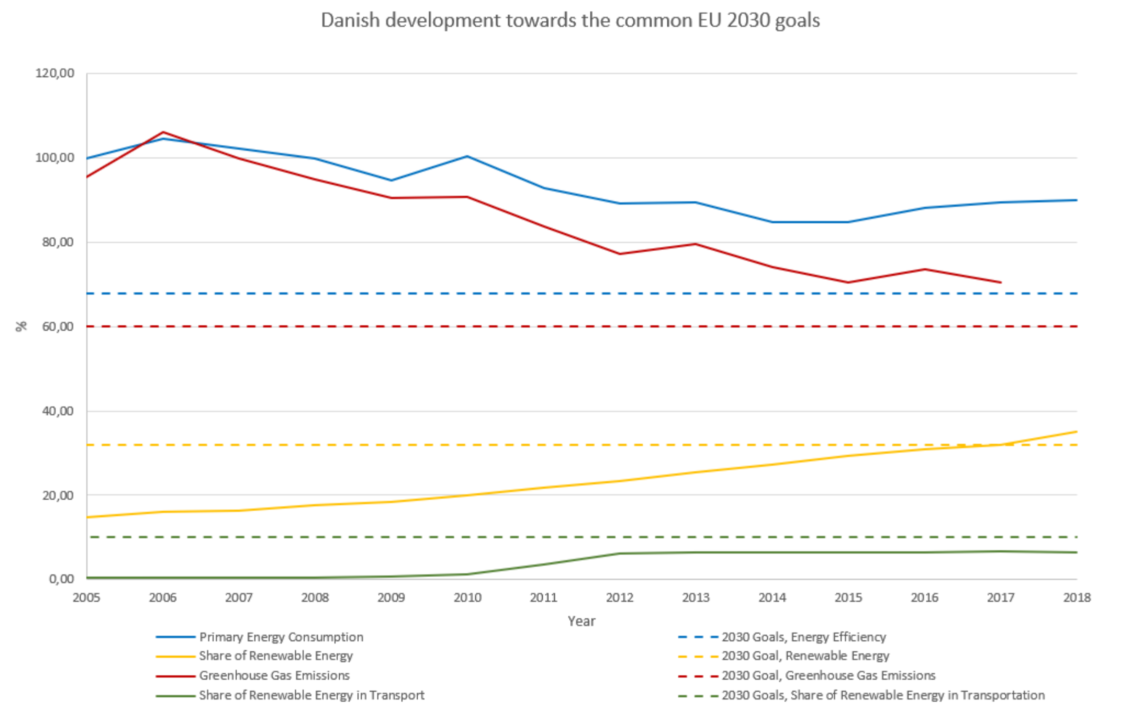


Figure 1.2: Own graph showing the Danish development towards the overall EU climate and energy framework goals for 2030. Primary Energy Consumption is indexed to 2005, while Greenhouse Gas Emissions is to 1990. (European Commission 2014*a*, Eurostat 2020*a*,*b*,*c*,*d*)

1.3 The Danish Energy System

The aforementioned ambitious energy and climate goals are setting a direction for the future energy system development in Denmark. There are multiple ways of reaching the goals and targets, given that different technology mixes can be used to increase the RES share and sustainability in the energy system.

The sustainable transition

The sustainability goals for the energy system are often subdivided into goals that concern each sector, such as electricity, heating, cooling, industry, and transportation. This is only natural, as the cost for CO_2 savings is different for each sector. For example, wind power is already competitive against fossil fuel alternatives in electricity generation while sustainable fuels for transportation are still expensive compared to their fossil fuel counterparts. Additionally, if the energy system sectors are integrated where heating and transportation are built upon electrification, the sustainability in the electricity sector needs to be developed prior to the others.

Overall a sustainable transition utilises and integrates RES in the different sectors, lowering the overall demand for fossil fuels by creating a more coupled system based on renewable resources. Based on this intention it is therefore important to ensure that an increase in e.g. electricity demand by electrification of sectors happens based on renewable electricity production. If the increase in electricity demand contrarily causes a combined heat and power plant (CHP) or power plant (PP) that runs on coal or natural gas to start, then the transition can not be considered to be sustainable, since it only displaces the CO_2 emissions to the electricity sector. This topic is also included in the EU's Renewable Energy Directive II (RED II), which e.g. states that to produce sustainable fuels to be used in the transportation sector, there has to be an element of additionality to the renewable electricity supply (European Union 2018).

In Denmark, electricity production already consists of a large share of RE which can be seen in Figure 1.3. Here it can be observed that electricity production from renewable sources accounted for the majority of all electricity production in 2017.

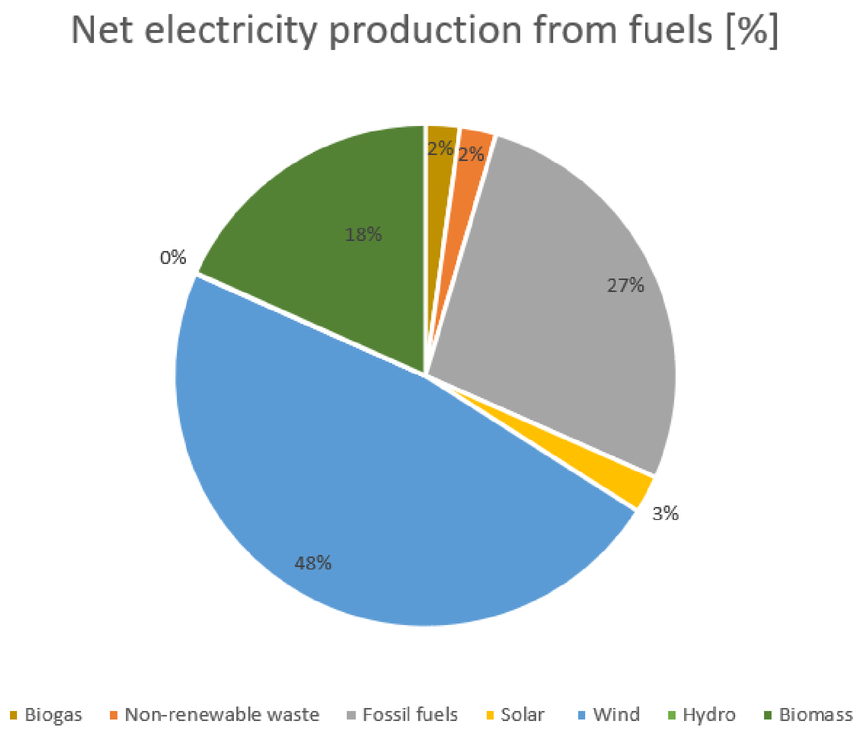


Figure 1.3: Production of electricity per fuel type in 2017. Here the group *Fossil fuels* include oil, coal and natural gas. Data used from (Danish Energy Agency 2020*b*)

The CO_2 emissions in 2017 for each sector is shown in Figure 1.4. Here the agriculture and transport sectors account for the majority of the emissions. The emissions in the agriculture sector are mainly from plant residue turnover and livestock manure while only a small fraction originates from machinery in the sector (The Danish Agricultural Agency 2020). Considering this, the transportation sector is observed as the largest emitter of CO_2 in the Danish energy system and therefore has a lot of potential for emission reduction.

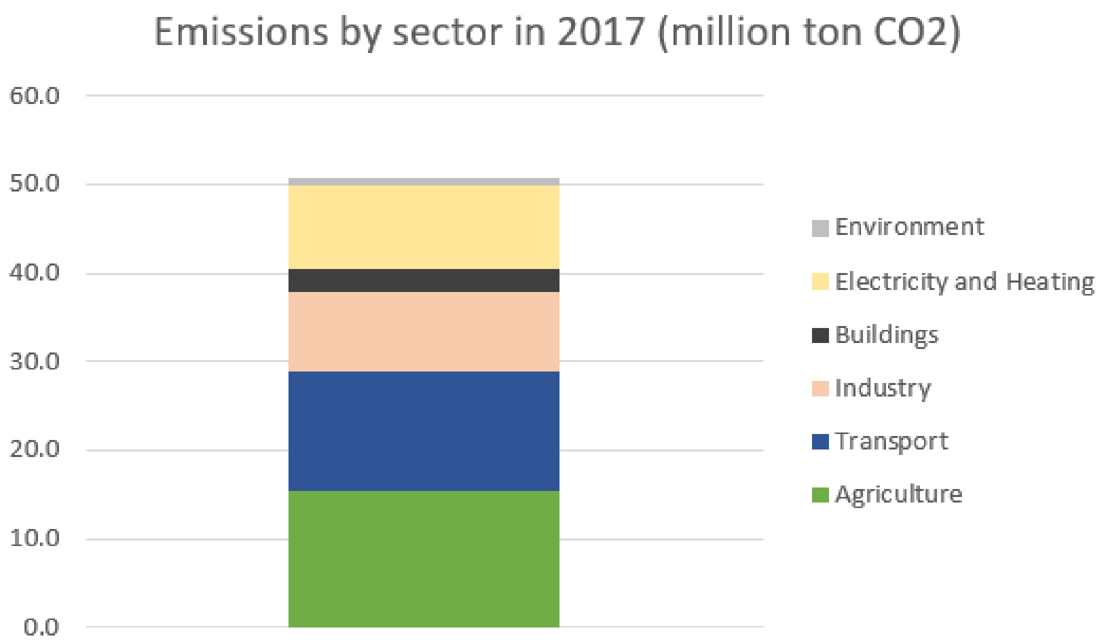


Figure 1.4: The emissions by sector in million tonnes of CO_2. Data used from (Klimarådet 2020*a*)

Understanding how the current energy system is composed can be an essential part of building scenarios that can help to illustrate and clarify future potential and possible developments of the energy system. In Figure 1.5 a simplified illustration of the Danish energy system in 2018 is outlined and shows the flow of energy and in which sectors the RES is being utilised. From this overview of the Danish energy sector and the emission numbers from Figure 1.4 it is observed that the transportation sector significantly needs to transition to comply with the goals at both the EU level listed in Figure 1.1 and the national goals listed in table 1.2. The transport demand from Figure 1.5 can be segregated into the transportation of persons and goods and the transportation mode which can be observed in Table 1.3.

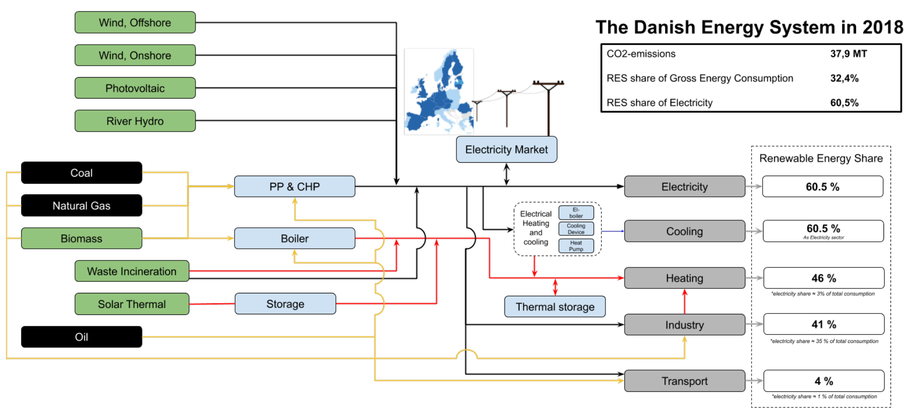


Figure 1.5: Own illustration of the Danish energy system in 2018 including the different RES shares for the consumption sectors (Danish Energy Agency 2018*a*)

Transport	Energy Consumption 2018		**[PJ]**	
	Person Transport		166.0	74.5%
	- Cars	65.1%	108.1	
	- International Aviation	23.6%	39.2	
	- Others (Rail, Ferries, Domestic Aviation)	11.3%	18.8	
	Freight Transport		55.1	24.7%
	- Trucks	43.9%	24.1	
	- Lorries & Vans (2-6 t)	44.3%	24.4	
	- Others (Rail, Ferries, Aviation)	11.8%	6.5	
	Total		**222.7**	

Table 1.3: Breakdown of the energy consumption in the Danish transportation sector in 2018. The military consumption ($< 1\%$) is not included and the breakdown is subject to uncertainty. (Danish Energy Agency 2018*a*)

Transitioning the transportation sector from fossil fuels to RES can to some extend be achieved by electrification through battery electric vehicles (EV), plug-in hybrid vehicles, electric trams and trains. As presented in Table 1.3 the total energy consumption in the transportation sector consists of approximately 96% fossil fuels which is expected to decrease to 92% in 2030 (Danish Energy Agency 2019*a*). The reduction in fossil fuels towards 2030 is mainly expected to ensue from an increased share of electric trains and electric cars in road transport. EV's and plug-in hybrids are projected to represent around 10% of the total amount of cars and lorries in Denmark in 2030. (Danish Energy Agency 2019*a*) The approximately 90% remaining cars and lorries in Denmark are still powered by fossil fuels which continuously is going to contribute significantly to the CO_2 emissions in the transportation sector.

To further reduce the emissions in the transport sector other methods are therefore also relevant. Integrating the electricity sector and utilising the large amount of renewable electricity generated in Denmark by creating sustainable electrically produced fuels, called electrofuels, can be a viable solution. This is also outlined, as a future potential in the aforementioned reports from both the Danish Energy Agency (DEA) and the Danish Society of Engineers (IDA), which can have a large effect on the future development of the entire energy system. These electrofuels are developed through an overall method of electricity conversion called Power-to-X, (PtX) where electricity is used to produce and refine hydrogen products into fuels. Additionally, to be used in personal vehicles, electrofuels can also be used in the heavy-duty long-distance transportation sector where electrification is considered less suitable (Ridjan 2015).

Another renewable alternative for the transportation sector is to produce biofuels from biomass. This option can however cause problems, as there are limits to how much biomass can be sustainably produced and used in the transportation sector. The biomass potential for Denmark is affected by the amount of available biomass at a national scale but also affected by e.g. food production and dietary choices in the rest of the world. Relying solely on biofuels may, therefore, exceed the limit of sustainable biomass available. As a consequence, biomass cannot meet the entire transport demand and replace the large amount of fossil fuel used in the transportation sector (Graves 2010). Electrofuels can therefore play an important role in the future energy system. The adequate development of the transportation sector can however be perceived differently which also can be observed in the IDA and DEA scenarios investigating the future Danish energy system where for instance biomass and electrolysis availability are different (Mathiesen et al. 2015).

DEA and IDA energy scenarios

The development and sustainable transition of the Danish energy system are conventionally investigated and considered through scenario analysis which is done by both governmental and non-governmental organisations. The Danish Energy Agency (DEA) does this too make sure that Denmark has enough energy now and in the future while the Danish Society of Engineers (IDA) also do it to show alternative pathways to ensure the same. The scenarios outlined by DEA and IDA are all created from a reference year of the Danish energy system and from there explore different pathways of development through different scenarios. The DEA report from 2015 on the *energy scenarios towards 2020, 2035, and 2050* describe four scenarios; Wind, Biomass, Bio+ and Hydrogen and consist of the whole energy system to ensure consistent development between the sectors in terms of available resources and energy conversion (Danish Energy Agency 2014). The main purpose of the scenarios is to outline the potential development pathways for the Danish energy supply towards a zero-emission society in 2050 and to outline the technical possibilities in the future Danish energy system. The IDA Energy Vision 2050 report from 2015 describes how a smart integration of the energy sectors in Denmark can create an energy system based on renewable energy (Mathiesen et al. 2015). The report, therefore, challenges the scenarios developed by the DEA and shows alternative pathways with a focus on cross-sectoral interaction. The report presents the scenario for; *a smart energy system strategy for a 100% renewable Denmark* that is presented to be technical and economically feasible and more resilient and robust compared to the DEA scenarios. However, none of the scenarios outlined by DEA or IDA are to be understood as detailed plans or accurate forecasts for the future. The scenarios are developed under some given assumptions and can be sensitive to small changes in the system parameters. Scenarios are nonetheless useful to expose challenges and highlight critical parameters and potentials which are important to consider for the development.

The DEA and IDA energy scenarios consider the future development of the transportation sector in Denmark. In the IDA 2050 vision, most of the transportation demand is covered by electric vehicles, a part is covered by biomass, limited to what can be produced from sustainable sources, and the rest by electrofuels (Mathiesen et al. 2015).

In the DEA scenarios there are two scenarios in which electrolysis is considered for the transportation sector: Wind and Hydrogen. In the Wind scenario, biomass is limited to an amount that could be locally produced and relies heavily on electrification. In the Hydrogen scenario, a smaller amount of biomass is required, but it has a higher system cost. On the other hand, the DEA scenario considers electric vehicles to a lesser extent and proposes the use of syn-fuels obtained from upgraded biogas. (Danish Energy Agency 2014) However, this requires a higher demand of biomass in the system. The installed wind and solar generation capacity for the different scenarios can be seen in Table 1.4.

Scenario	Wind Onshore (MW)	Wind Offshore (MW)	PV (MW)
IDA 2035	3,875	5,887	3,127
IDA 2050	5,000	14,000	5,000
DEA Wind 2035	3,500	5,000	1,000
DEA Wind 2050	3,500	14,000	2,000
DEA Hydrogen 2035	3,500	6,000	1,000
DEA Hydrogen 2050	3,500	17,500	2,000

Table 1.4: The wind and solar photovoltaic (PV) capacities in the different DEA and IDA scenarios (Danish Energy Agency 2014, Mathiesen et al. 2015)

In all of the aforementioned scenarios, there is a considerable increase in capacity for fluctuating renewable electricity production. Part of the extra RES capacity is used to supply hydrogen production in the 2050 scenarios. For the IDA scenario, an electrolyzer capacity of 7.5 GW is considered, while the DEA Wind has a capacity of 2.4 GW and the DEA Hydrogen one of 3.5 GW. Increasing the electrofuel production in the scenarios enables them to reduce the biomass demand for the transportation sector. The future outlined in these scenarios therefore envisages a large capacity of PtX as part of the Danish energy system. The large potential for PtX in Denmark is due to the good conditions for wind power. Therefore, PtX can play an important role in reducing the CO_2 emissions from the transport sector under the assumption that they are produced using renewable electricity.

1.4 Power-to-X

Power-to-X, or simply PtX, is the broad term used for the conversion of electrical power to a physical fuel or other types of power, such as heat. The first step in the process of converting electricity into fuel, either in a liquid or gas form, requires the separation of hydrogen from water molecules via electrolysis. This process requires electricity and water. From this, the hydrogen can be used directly for power generation or converted into other PtX products such as methanol or methane. The further conversion of hydrogen happens through various chemical processes by turning the hydrogen into larger molecules which then can be applied in various energy technologies. Hydrogen is as such a PtX product itself but also the reactant for the creation of other PtX fuels.

The production of hydrogen can also be done by using natural gas, other fossil fuels, and bio-based sources, where the hydrogen atoms are separated from the hydrocarbons. While the production of hydrogen via electrolysis has the possibility of making the production process emission-free the more conventional process using natural gas is currently more widely used, which is mainly due to low efficiency and high capital cost for hydrogen produced via electrolysis (Nikolaidis & Poullikkas 2017). Creating hydrogen from fossil fuels can create a problem with the sustainability of the product since this not is environmental sustainable due to the CO_2 content in natural gas. The trend in hydrogen production has nevertheless changed in the last decade where an overall increase in demonstration projects using electrolysis has been observed worldwide (Chehade et al. 2019). Using electrolysis to create hydrogen can then be environmentally sustainable if the electricity supplied originate from RES.

A review on PtX demonstration projects by Chehade Et al. (Chehade et al. 2019) investigates various demonstration projects worldwide and suggests that PtX can be categorised as six main pathways from the process of producing hydrogen via electrolysis. These are presented in Figure 1.6 where the utilisation of the different pathways are outlined to show where PtX products can help to reduce emissions from fossil fuels in society. The *fuel* pathway in Figure 1.6 is where the transport sector is situated which previously was mentioned having a large potential in order to help towards the political goals in the future.

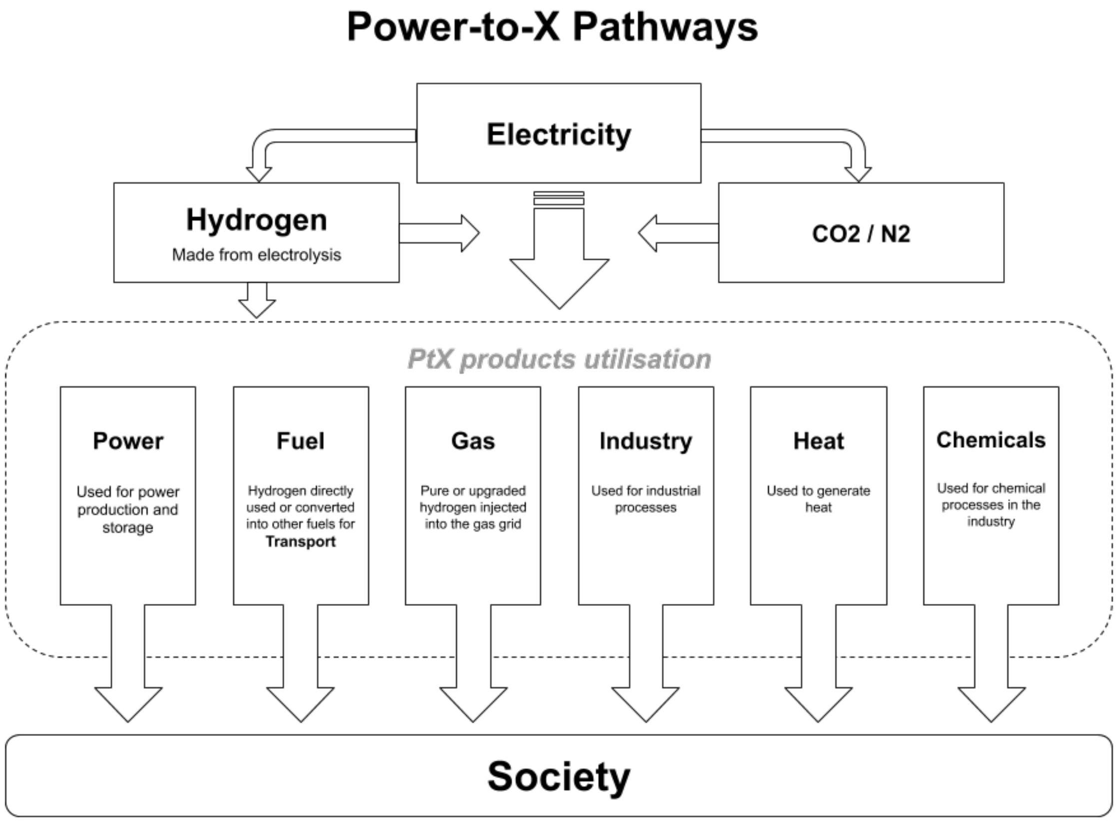


Figure 1.6: Own illustration of the PtX pathways based on Chehade et al. (Chehade et al. 2019)

Furthermore, the use of PtX is increasing as observed in Figure 1.7, where the different pathways and their time for commencing are presented. From Figure 1.7 it is seen that the majority of projects currently conducted are those using PtX to create power. This is the case because the majority of these projects have been started before 2009. However, it is observed that in the recent decade PtX projects producing gas and fuel have represented the majority of started projects. It should be noted that some of the projects are used for multiple applications; an example of this is a PtX project creating both power and heat, thereby functioning as a central heat and power plant.

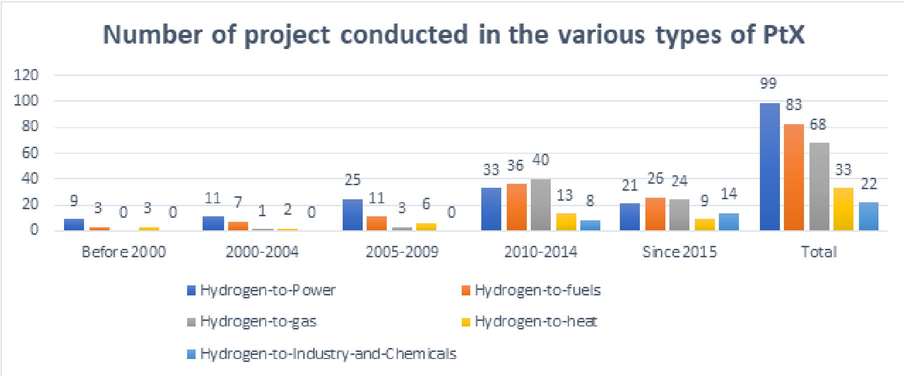


Figure 1.7: An indication on the type distribution of the various PtX application for the last two decades. Data used from (Chehade et al. 2019).

The geographical spread limited to continents are presented in Table 1.5 where it is observed that the majority of projects conducted are located in Europe. This marks Europe as the main driver for the development of the PtX industry. This drive potentially originates due to the European commitment to fulfilling the energy goals and the role PtX can play in storing renewable energy (European Union 2020). Funding for research from the EU and more specifically the *Fuel Cells and Hydrogen Joint Undertaking* (FCH JU) (Fuel Cells and Hydrogen Joint Undertaking 2020) and the creation of the association; Hydrogen Europe (Hydrogen Europe 2020) has also helped to develop Europe's leadership on the matter. Despite the limited amount of commercial-scale plants, a study by Decourt (Decourt 2019) suggests that PtX is now attracting more entrepreneurship and could be expected to approach a technology readiness level (TRL) high enough for it to become market-ready in the near future.

Geographical placement	**Number of projects**
Europe	154
North America	18
Asia	13
Oceania	5
South America	2
Africa	0

Table 1.5: (Chehade et al. 2019)

Real applications of PtX technology already exist in Denmark where 14 projects currently are active while 5 already have been completed. These projects are listed in Figure 1.8.

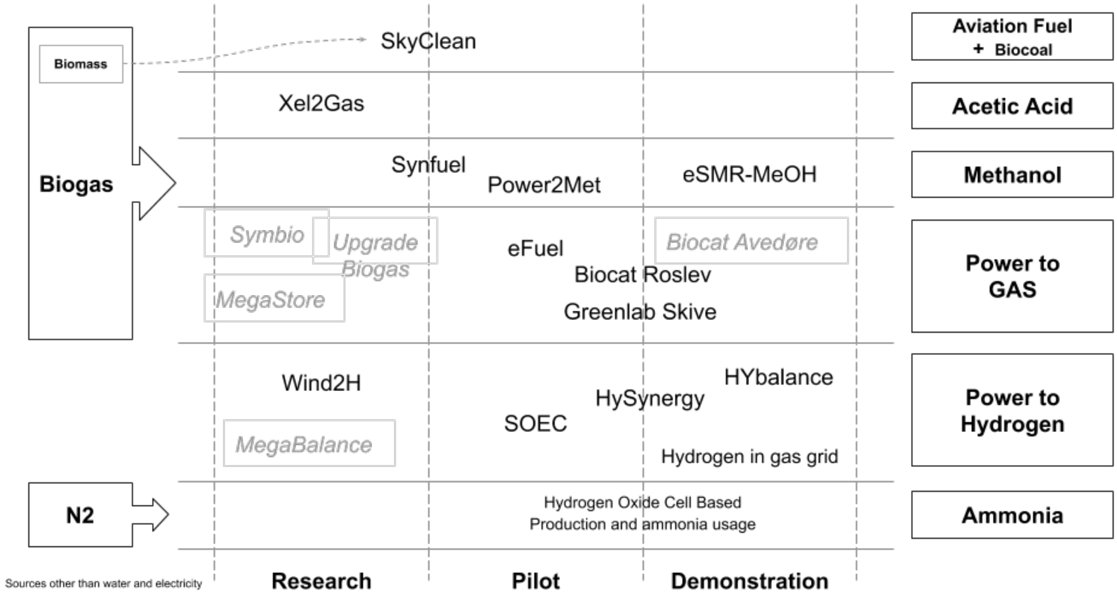


Figure 1.8: Own illustration of the PtX projects in Denmark up until February 2020. Entries with grey indicate completed projects (Jørgensen 2019). All projects use hydrogen unless other is specified.

The products from Figure 1.8 are generated through research-, pilot- or demonstration-projects why the electrolyser unit capacity in these projects all are small. Noticeable are the *Greenlab Skive* (12 MW) and the *HySynergi* (20 MW) project which are the largest capacity electrolysis projects in Denmark so far. These projects received funding through *Energiteknologisk Udviklings- og Demonstrationsprogram* (EUDP) in the fall of 2019, on a scale of 128 million DKK. (Danish Energy Agency 2019*b*) This emphasises the interest of developing PtX in Denmark but also that the projects at this point are not economically feasible. Decourt (Decourt 2019) suggests that this is because the market information and market readiness are missing for this technology.

One of the promising PtX products to be used in transportation is methanol. In addition to being used purely in methanol fuels cell, methanol can also be mixed with gasoline and used in combustion engines. The usable mix would correspond to 3% of the total gasoline amount, even though the current framework dictates that only ethanol alcohol can be used for mixing with gasoline. It has however been proven that a mix of methanol (3%), ethanol (5%) and gasoline (92%) can provide an emission saving to the fuel usage. Additionally, a mix of 85% methanol and 15% petrol has been tested with minor engine modification, where the results showed increased engine efficiency as well as the possibility of lowering the emissions based on the methanol source. (Winther 2019)

This chapter outlines the potential of PtX to be a sustainable alternative to fossil fuels in the transportation sector which consequently can help the sector towards a more sustainable future. However, a major barrier for this technology is the lack of economic sustainability linked to the projects in a Danish context and the market readiness of the technology. The previous projects have mainly been investigated from a business point of view, not addressing the socioeconomic gains linked to these facilities. This project onward focuses on producing the PtX product methanol due to its relatively simple composition and its advantages when utilised in the current transportation system. Moreover, methanol can be further utilised to generate more complex fuels such as electrofuels used in shipping and aviation. Developing PtX could potentially make Denmark take leadership in the sustainable transition.

Problem Formulation 2

Throughout the previous chapter, PtX and its potential role in the Danish energy system has been presented and explained. PtX can both be the necessary solution to reduce the emissions from the transportation sector and act as an energy storage for an electricity system with a high percentage of renewable fluctuating electricity production. PtX can therefore potentially help reach the goals set by the Danish government, in regards to the emission reductions, and electrify the transportation sector, which emits a high share of the Danish CO_2 emissions. Despite the potential of PtX, it is still not a widely used technology. This is mainly due to the general low technology readiness level and the fact that its products are not able to compete with the price of their fossil-based counterparts. Given that PtX facilitates the production of sustainable alternatives to fossil fuels, this report aims at investigating the socioeconomic effects of implementing PtX in the Danish transportation sector. This is done under the following research question:

How can the potential socioeconomic effects of implementing Power-to-x for transportation before 2030 in Denmark be applied?

To develop an adequate research design for the various aspects of the research question needed to be enlightened, a set of sub-questions are developed:

- Who are the relevant stakeholders and how do they affect the implementation of PtX in Denmark?
- What are the socioeconomic benefits of implementing PtX?
- What are the parameters affecting the socioeconomic feasibility of PtX in a Danish context?
- What PtX solution is most easily applicable to the Danish society before 2030?

To answer the research question a series of limitations to the research are introduced in the following section, in order to scope the research and create an adequate frame for the report.

2.1 Limitations

The project limits itself to only investigating the societal potential of PtX in Denmark. This means that the results achieved in this project are only applicable in a Danish context. They can however give an indication of the effects achieved in other countries with similar energy systems and political framework as Denmark.

In order to find the socioeconomic effects of PtX in Denmark, an energy system analysis is conducted. This is done to determine the revenue, costs, efficiencies, and emissions created by producing electrofuels. One of the crucial inputs for the PtX plant is electricity and an increased capacity on the electrofuel plants will evidently put a higher demand on the electricity-producing part, of the Danish energy system. This demand is only considered to a certain point being the risks of bottlenecks within the electricity grid. In order to accommodate this and avoid bottlenecks, the size of the plants modelled is designed accordingly.

Another potential issue with expanding the demand on the electricity sector is the risk of superseding the RES present in the system, and with that create a higher CO_2 emission from the electricity production than originally seen. While this should be considered when designing an electrofuel plant on a large scale, this report assumes that the renewable electricity sector will expand at a pace where it is able to accommodate the electricity demand of the electrofuel plant, without exceeding the RES present in the system.

Additionally, PtX requires a water source to conduct electrolysis. Having extensive water usage could potentially exceed the water reservoir, and add a requirement for expanding water extraction for the Danish society. This is not addressed in this report, as it is assumed that the available water sources in Denmark are considerable, and therefore not exceeded. In relation to this both the emissions of extracting water, meaning the electricity for pumping water from the ground, and the price of the water used is not be given a socioeconomic cost either since this is deemed negligible compared to the other expenses of the PtX plant.

Various pathways can be taken in order to estimate the socioeconomic price of CO_2 emissions. In this project, this value is based on the report by Carbon Pricing Leadership Coalition (Carbon Pricing Leadership Coalition 2017), that estimates the price of mitigating the carbon emission by 2020 to be 40-80 *USD* pr. ton CO_2, corresponding to 36.8-73.6 euro pr. ton. This estimation does however only include *immediate effects*, *acceleration of technological change* and *short-term knock-on effects and long-term development benefits*(Carbon Pricing Leadership Coalition 2017). Summarising this can be defined as the economic and environmental value of reducing CO_2 emissions, whereas the social cost of CO_2 would include the price as a consequence of not avoiding the CO_2 emissions. This price is considered adequate since the positive contribution of implementing electrofuels on the scale suggested in this project is deemed hard to evaluate in the terms of environmentally damage avoided. Other environmental effects such as NO_X, CH_4, SO_2 and SO_4 emissions are not investigated in this project, meaning that the evaluation only includes the climate effects of replacing fossil fuels with electrofuels. This approach is taken since it is complex to quantify the cost of the environmental and especially the social health effects.

CO_2 sources are required to produce methanol via PtX. The only CO_2 sources focused on are those coming from biogas plants with gas grid upgrades, as these are considered to be the most easily accessible CO_2 sources in Denmark. These Co_2 emissions are considered pure enough to be used directly in the electrofuel plant without further purification.(Danish Energy Agency 2017) Other types of sources could be used, such as carbon capture on point sources in the industry, but these were estimated to increase the electricity demand of the system and with that lower the overall efficiency of the plant process.

Other technologies such as second-generation biofuels and EV's are also able to contribute to decreasing the emissions of the transportation system, and with that evidently fulfil the objective of the electrofuels in this report. These are not considered when evaluating, since the focus of this report is the prospects of producing and using electrofuels, and not solely decreasing the emissions of the transportation sector.

The *Tax Distortion*, which is applied in the danish context to socioeconomic calculations as a standard (The Ministry of Finance 2017), is discarded from this report. This element is left out because it is assumed that previous taxes already have created distortion why the market can not be observed as a *new* free market in optimal balance. A precondition for the *Tax Distortion* is also that all externalises are internalised in both cost and demand. (Hvelpund 2015) This is not the case since NO_X, CH_4, SO_2 and SO_4 emissions not are included in this report and often not assigned a monetary value in reality as well. Furthermore, the Danish society is a democratic society, why citizens who participate through fiscal and political institutions are generating fiscal outcomes endogenously. (Wagner 2002)

The report presents all values in socioeconomic prices why the values are not converted to market prices using the *nettoafgiftsfaktor*. This factor converts values from socioeconomic prices to market prices, adding taxes and subsidies to it. Since this report investigates how the socioeconomic elements of a PtX solution impact the feasibility study, this conversion is not needed.

Theoretical Framework 3

In this chapter, the overall theoretical approach to the problem is presented which helps to set the frame for the report. This is done to support the analysis in this project and to reach a more comprehensive understanding of the reality which the research question is situated within. The theoretical framework is developed before the analysis why this framework helps to establish an adequate scope for the investigators to reach a deeper understanding of the problem. This is assisted by understanding how an energy system can transition through knowledge of technological change and how this can be enabled through choice awareness. A more profound understanding of the market economy and the institutions is furthermore outlined in this chapter.

3.1 The Adequate Framework

The theoretical framework for this report is inspired by the theoretical approach in *Electricity Reforms, Democracy and Technological Change* by Hvelplund (Hvelplund 2001), where the framework is established by the adequate macro- and micro-structures and linked together. Developing this adequate framework establish from where the investigator departs regarding the questions to be analysed. The investigator performs an analysis through theories and a structure of reality which affect the analysis and consequently the results. The adequate framework is therefore clarifying and scoping the research area for the analysis.

The adequate framework is underlying a set of governing policies which has created the current reality and the particular circumstance in which the research question is investigated. This adequate structure of the reality can be referred to as the *first order governance system* which are the basic condition and structures in society. This system is constructed by the governance systems and institutional structures which are present in the given time where the investigation of the question is performed and can only be changed throughout political processes on a long term basis. Based on the Problem Analysis in chapter 1 the current reality of the PtX scene in Denmark can be considered a novelty despite the technology being proven. This is also observed in the current regulatory framework for PtX which is not existing since no direct laws and legislation's are made for the PtX sector. The sector is nevertheless indirectly affected by the laws and legislation's on other sectors and areas such as mixing ratio for fuels, injections of gas standards, tariff-structures and the issue of guaranteeing the sustainable certification for sustainable PtX products (Brintbranchen 2018). Outlining the overarching framework for PtX in Denmark, as a *second order system*, therefore reveal the relevant elements and the relative macro-structures which impact the

PtX sector in Denmark. The *second order system* is underlying the aforementioned *first order system* which also is illustrated in Figure 3.1 where the adequate macro-structure for PtX in Denmark is outlined. The potential macro-structures for a *second order system* can be claimed to be infinite unless a scoped set of specifications are created. These specifications are created by the goal hierarchy from Figure 3.1 and the related action organisation for PtX in Denmark which scopes the relevant macro-structures to the research question.

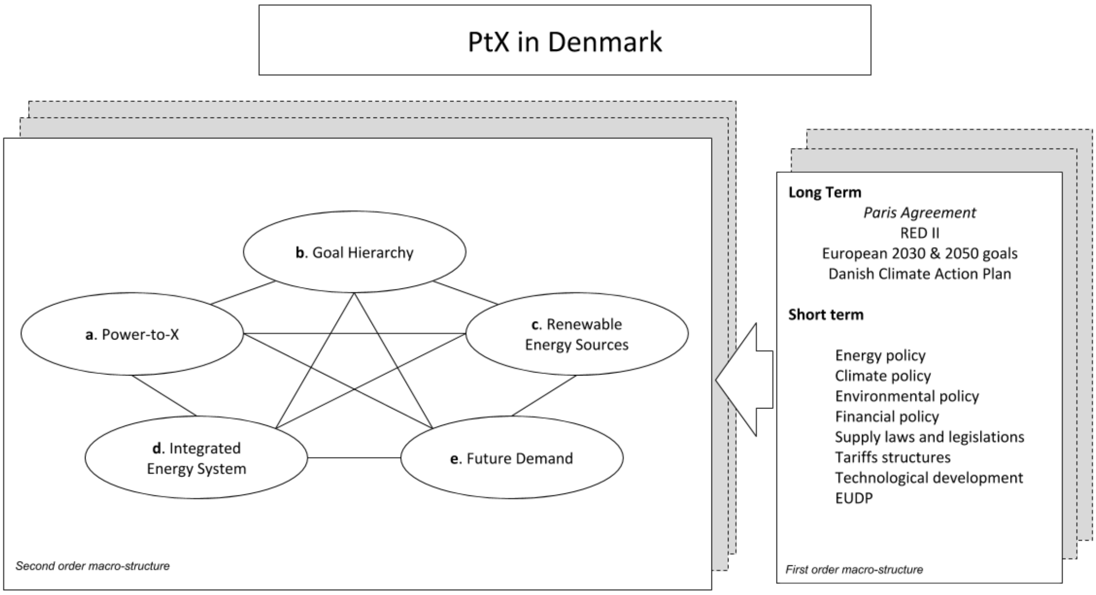


Figure 3.1: Own illustration adopted from Hvelplund (Hvelplund 2001) of the adequate macro-structures in the first and second order system in relation to PtX in Denmark. The grey stippled boxes indicate that an infinity number of other macro-structures exist and can be outlined depending on the question investigated.

Introducing the associated first and second order system enable a more structured understanding of the problem which permit the investigator to scope the analysis adequately to answer the research question. The establishing of the adequate system can as such qualify the results and the discussion which is related to the following statement:

> *PtX in Denmark **(a)** can be an important technology in means to reduce CO_2 emissions **(b)** by using outputs from RES **(c)** to integrate RE in all sectors of the energy system **(d)** to meet future demands **(e)**.*

The relevant information to answer the elements in the *second order system* are now seen in Figure 3.1 as macro-structures which clarify what information is relevant to address in relation to the research question. From this, it becomes clear that the current deployment of the PtX technology in Denmark (a) is relevant to examine and access to determine what the potential of it is in this context. To understand the potential of PtX to reduce CO_2 emissions (b) it is relevant to outline the current goal hierarchy which is determined by the overall governmental goals and inputs by stakeholders in Denmark.

The relevant regulatory framework is therefore also important to address. This has to be considered in relation to outputs from RES (c) where the definition of sustainability and renewable technologies have to be considered together with the development of RES and the relevant infrastructures. The relevant aspects of the integration of RES in the energy system (d) is other possible technologies, which can be a threat to PtX, the composition of the energy system and how PtX can be utilised in the energy system and increase the RE percentage in the whole system. Another important aspect for this is the future demand (e) for not only PtX products but also the entire energy system on a national scale.

In Figure 3.2, the second order macro-structure for PtX in Denmark presents the micro-structures and the institutional interrelations between the entries. The figure shows how different aspects are interconnected by micro-structures and thus provide clarity to the inputs and outputs relevant to developing PtX in Denmark. It is also observed how the overarching EU level impacts the local level in Denmark through the national institutions and their micro-structures. An essential consideration when producing PtX in Denmark, is the distance to existing energy infrastructure.(Nielsen & Skov 2019) This should therefore also be considered and included at the local level. Furthermore, existing infrastructure also creates possibilities or limitations depending on what product is being created in terms of storage and distribution of the potential PtX product. As observed in Figure 3.2 the goal hierarchy, historical situation, and external interrelations are also affecting the current PtX scene in Denmark and can subsequently affect how the future of PtX in Denmark develops. It is important to notice that Figure 3.2 is situated within Figure 3.1 and therefore impacted by the overarching macro-structures in both the first and second order system.

The second-order system is therefore important to understand since it reveals how a change in the PtX scene in Denmark affects the adequate framework for this report. This furthermore reveals where change can happen and how this then impacts the adequate framework through the macro- and micro-structures from Figure 3.2. This creates a more comprehensive understanding of the reality as it is observed and scoped for this report. The adequate framework furthermore helps to clarify the PtX sector and limit the scope of what is suitable and deemed as relevant for the research question. The effects of the various macro- and micro-structures on the PtX sector development in Denmark can vary significantly in importance depending on the stake embedded in the specific stakeholders and institutions. With this in mind, it is therefore important to address how the future of PtX can be affected by these stakeholders and their specific perception of reality. An essential part of this is the theoretical background for the current economic understanding and reasoning together with the understanding of the influence of institutions embedded in the adequate framework.

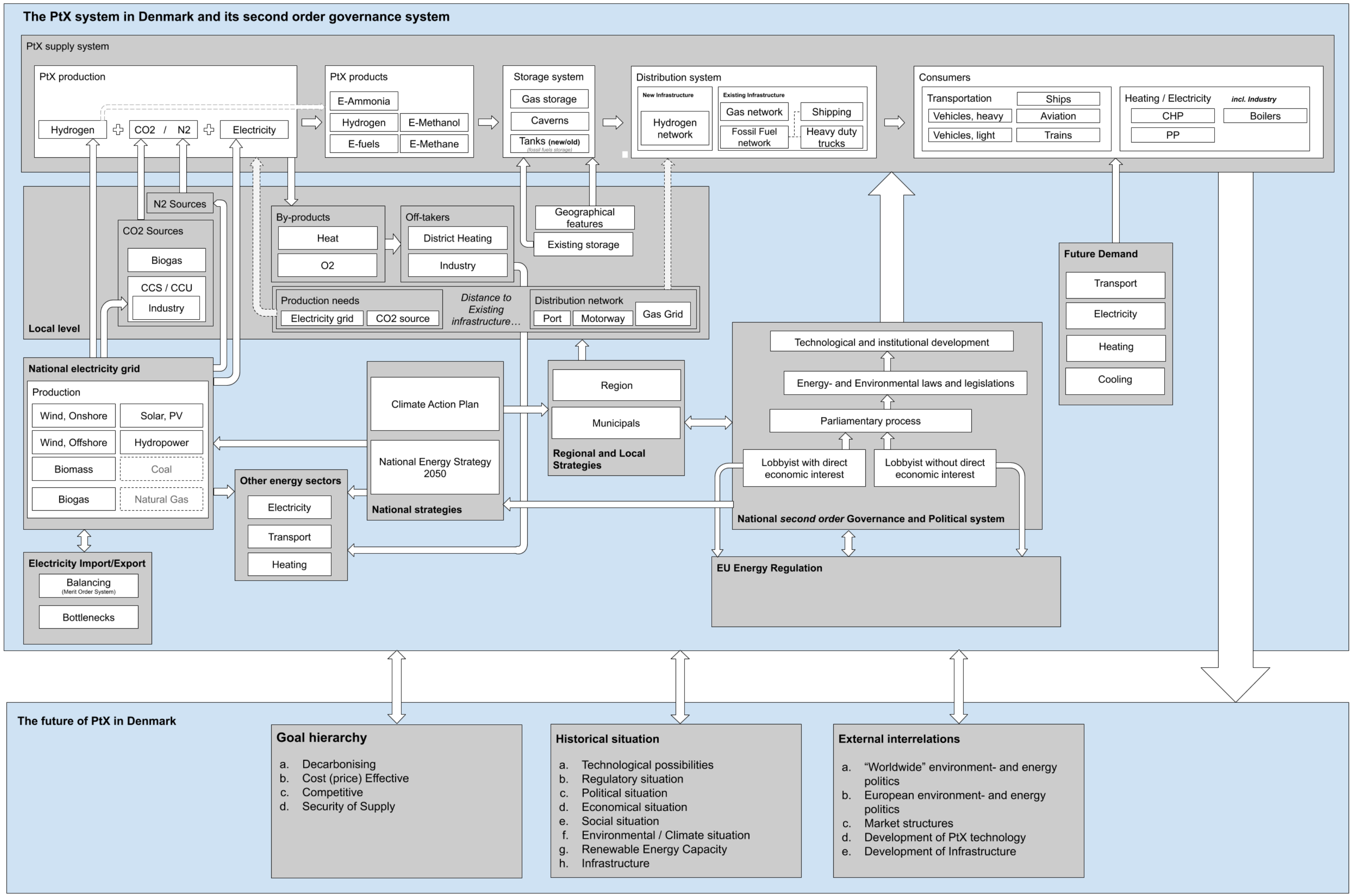


Figure 3.2: Own illustration inspired by Hvelplund (Hvelplund 2001) of the adequate second order system with the macro and micro-structures for PtX in Denmark showing the institutional interrelations.

3.2 The Transitioning Energy System

The adequate framework relevant for PtX is situated within the Danish energy system as presented in Figure 1.5 on 7. In table 1.2 on page 4 it becomes clear that the Danish energy system is transitioning towards a 100% RE system which include several substantial challenges where PtX can be seen as one of many solutions to this. To comprehend how a certain solution fit into the given context it can be useful to understand which phase of the transition the energy system has reached. This can help to identify the criteria for the strategic measures and technical requirements relevant in the current phase for the transition of the energy system. An energy system can according to Lund (Lund 2014) be classified into three different phases moving towards an independent RES based system based on the implemented and utilised RE share. Based on this understanding the three phases of the transition of an energy system can be outlined as in Figure 3.3.

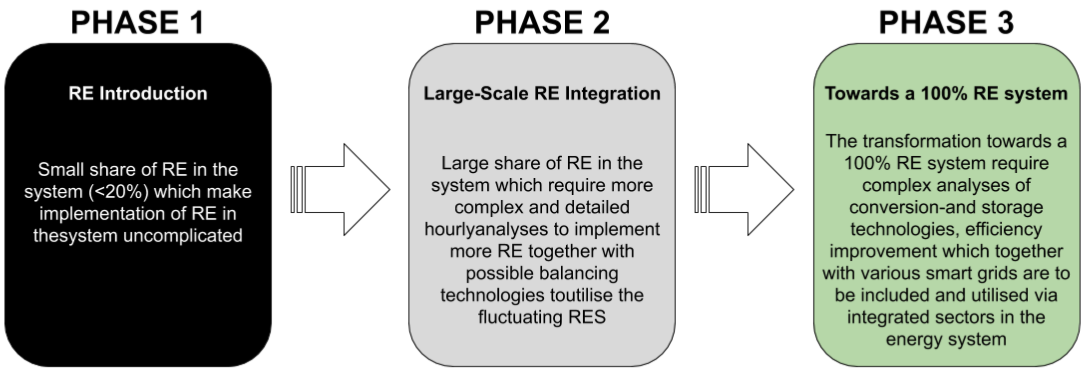


Figure 3.3: Own illustration inspired by Lund (Lund 2014) of the three phases of the transition of an energy system.

The definition of a transitioning energy system from Figure 3.3 can be projected onto the Danish energy system as illustrated in Figure 1.5 on page 7 to clarify what is needed in the further transition towards a 100% RE system. Based on the system outlined Figure 1.5 and the breakdown of the RE share in the different demands the Danish energy system can be classified as a late *phase 2: Large-Scale RE integration* or an early *phase 3: Towards a 100% RE system*. This classification is reasonable since large shares of RE is integrated in the electricity, heating and industry sector as presented in Figure 1.5. The integration of RE is however an ongoing process and at the same time a smart utilisation of the available RES across sectors is currently a focal point. This can be observed in the strategies behind the Danish energy agreements presented in table 1.2 on page 4 where both expansion of RES and sector integration is outlined as important for the future. The importance of whether or not the Danish system is classified phase 2 or 3 can, however, be questioned. The classification provides considerations towards strategic measures and technical requirements relevant but for a system like the Danish energy system, the consideration from both phase 2 and 3 are relevant. Nonetheless, the classification of the system provides an adequate assessment of the strategic measures and technical requirements relevant which also provide information for the potential needs for a modelling tool.

For the investigation of a the PtX solution, the modelling tool, therefore, has to be able to do a detailed hourly simulation of inputs such as electricity, CO_2, hydrogen conversion and further processing, storage of the products and efficiency improvements. Structuring an adequate energy model based on these principles therefore enable an investigation to include and test the PtX solution in a system transitioning towards a 100% RE system.

In regards to the research question and the context of the report, a technological change is required within the Danish energy system since PtX technology is still a novelty technology in the system according to section 1.4 on page 1.4. A more profound and comprehensive understanding of technology and how a change in technology can happen is therefore relevant.

3.3 Technological Change

From a holistic point of view technology can be divided in the four main components; *technique, knowledge, organisation* and *products*. These can be defines as:

- **Technique** is the joining of technique, labour objects and labour processes
- **Knowledge** is the joining of ability, insight and intuition in the labour process.
- **Organisation** is leadership and coordination of labour in the work process
- **Product** are the outcome of the work processes which represent user value.

These four components are all connected and changes in one of these components endure a change in all four components. When technology is observed in a societal context the main components are furthermore linked with changes in society. (Müller et al. 1986) This can be illustrated as in Figure 3.4 which show how changes in one component of technology can change components in society and vice-versa.

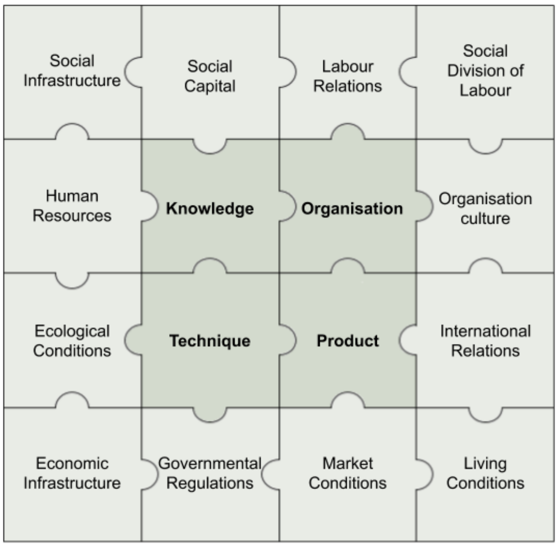


Figure 3.4: Own illustration of the link between technology (technique, knowledge, organisation and products) and society from Müller et al. (Müller et al. 1986). The purpose of the illustration is to show that all the components influence one another while the position of the individual jigsaw pieces are irrelevant.

Figure 3.4 provide a more thorough and holistic understanding of technology and also enhance the understanding of the complexity related to a change in technology from a societal point of view. The compliance in between the pieces of Figure 3.4 are constantly changing and depending on the characteristic of a given change, it can cause a *radical technological change* in the system. The term *radical technological change* is addressed by Hvelplund (Hvelplund 2018) who added a fifth dimension to the definition of technology in form of the component *profit*. Departing from this definition, a radical technological change is defined as a substantial change in more than one of the five components of technology. (Hvelplund 2005) But it can be argued that a successful radical technological change can impact all the other components in time since all of these are interlinked as illustrated in Figure 3.4. On the other hand, new technology can be abandoned over time if it is not able to create a substantial change. This can happen as a result of the given historical and institutional context in which the new technologies must be developed. Radical technological changes are therefore competing and compared against established technologies which have developed over time in the existing political and institutional framework. (Hvelplund 2018) This is illustrated in Figure 3.5 which show the interaction and influence by the existing premises of the framework. This emphasises the importance of the organisation component.

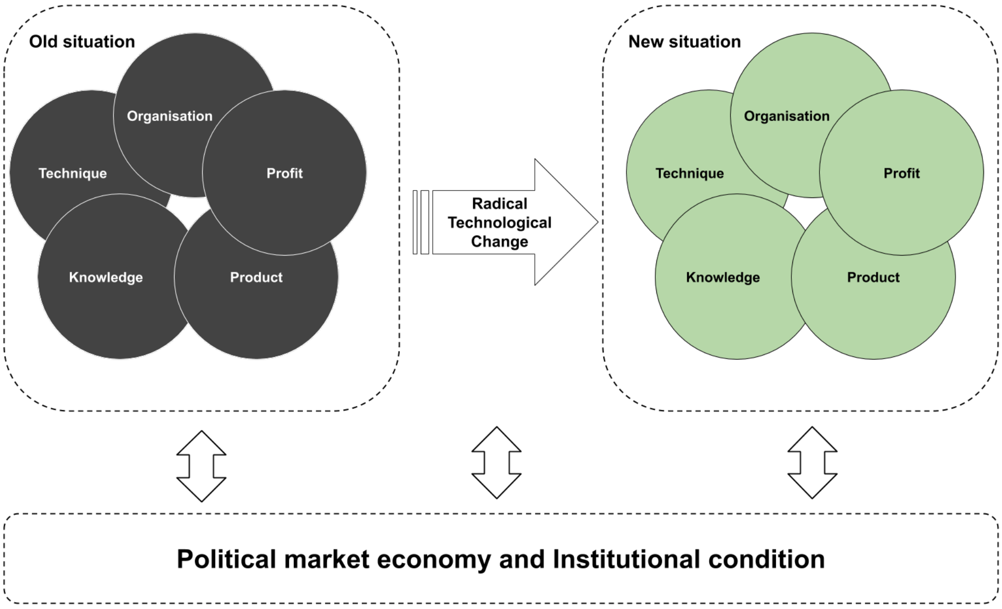


Figure 3.5: Own illustration inspired by Hvelpunds (Hvelplund 2018) definition of technology and the interplay with political market- and institutional conditions which affect the process of radical technological change.

Radical technological change can be seen as development which is affected by the political and economic theory embedded in the energy policies in the relevant context (Hvelplund 2018). The dimensions of the prevailing market economy and the current institutional conditions therefore becomes important. Based on this understanding the investigation of PtX requires a radical technology change to deploy in the Danish context. The focal point within this radical technological change can with help from Figure 3.5 be outlined to be; product, organisation and profit.

In addition to this, the expansion of technology provides information on how the difficulty of changing technology in the existing system. To provide more knowledge on how radical technological change in an existing energy system can be achieved the theory of Choice Awareness can be examined.

3.4 Choice Awareness

The theory of Choice Awareness is presented in the book *Renewable Energy System* by Lund (Lund 2014) and is built up by two theses concerning how radical technological change in an existing energy system can be achieved. Choice awareness theory is focused on the implementation of radical technological change in the existing organisations and institutions. This is investigated through theories on discourse, stakeholder and power from the point of view that existing institutions and organisations try to eliminate certain choices in the political decision-making process to preserve own interests. (Lund 2014)

The first thesis of the Choice Awareness theory outline how the social relations affected by discourse-, stakeholder- and power theory are affecting the decision-making process and the outcome of the final decision regarding major institutional changes. This can be used to promote certain choices and eliminate alternative choices or institutional changes. The second thesis of the Choice Awareness theory focuses on the fact that alternative choices can be promoted. This is done through a realisation that choices exist and can actually be chosen. Promoting these alternative choices through new strategies, plans and projects on all levels in society aim to create consciousness about the actual choice of a radical change and how these can be realised. This is summarised in the following four strategies (Lund 2014):

- Describe and promote concrete alternatives.
- Assess relevant economical objectives for society and include these in the feasibility studies.
- Suggest concrete changes via public regulation.
- Understand that political decisions do not occur in a political vacuum.

The theory of choice awareness as such outlines the important elements to consider and include in a feasibility study investigating a radical technology change. The importance of socioeconomic parameters is emphasised to promote alternatives which potentially can benefit society more than the traditional available choice's. To understand how choices are affected in the decision-making process a more thorough understanding of the current market economy and institutions in the context of the research question has to be considered.

3.5 Market Economy and Institutions

The economic theory applied in a society results in different interpretations and institutions affecting democracy, economy and politics. It is therefore important to understand from which economic paradigm the report theoretical framework is understood to examine the market and the institutions in which the research question is situated. Framing the economic understanding for the report prior to the analyses enable a more comprehensive understanding of the premises for the economic investigations, how the market and institutions are impacting society and how to interpret the results. According to Hvelplund (Hvelplund 2013) three contending political economy paradigms have been and are currently seen in the Danish energy policy context:

- The neoclassical approach
- The concrete institutional approach
- The innovative democracy approach
  (Hvelplund 2013)

The present Danish market economy has to a large extent been influenced by the ideas from neoclassical theory, which is based on the concept of a free market where the economy is in an optimum (Hvelplund et al. 2007). The fundamental assumptions for Neoclassical theory are denoted by Weintraub (Weintraub 2013) to be the following:

- People have rational preferences among outcomes
- Individuals maximise utility and firms maximise profits
- People act independently on the basis of full and relevant information
  (Weintraub 2013)

Based on these assumptions the neoclassical economy, therefore, sees the market in a state of optimum based on full information and the many mutually independent suppliers and buyers which due to demand and supply creates an optimum. Except for certain externalities which are internalised, the democratic participation in the market should be kept at a minimum, since the undisturbed market automatically will ensure in the best possible situation. (Hvelplund et al. 2007) The externalities are internalised in the energy prices via e.g. carbon quotas which are publicly regulated through CO_2 caps and trade systems and some taxes on CO_2. The public regulation via energy policy is correcting minor market failures since the market economy is in an optimum. In this approach, a change in technology can occur when a new technology is ready to enter the market and be competitive. (Hvelplund 2013)

This paradigm is also the foundation for the *cost-benefit* and *cost-effectiveness* analysis which uses monetary values for costs and benefits to compare projects as part of the decision making. This is done through current market prices and a discount rate which enable comparison of projects with different time horizons. (Hvelplund et al. 2007) The neoclassical understanding has furthermore endured in the concept of *tax distortion* in the danish context which is the marginal societal cost that is used in socioeconomic calculations to incorporate potential tax increase or decrease that can need to be funded through taxes (The Ministry of Finance 2017).

Besides the neoclassical economy theory, the danish market economy can also be observed to be affected by the concrete institutional economy. This is a technocratic approach Where the neoclassical economy represents the free market and the concrete institutional economy represent the concept of the real market. The real market recognises that the market is embedded in a historical and conditional market where politics are influenced by strong and influential institutions and their stakeholders. This limits the democratic process to certain influential institutions since the democratic process in this paradigm is designed under influence by these institutions, which are seen as experts, even when it comes to technological change. The influential institutions are often historical dominating institutions who have influenced the considerable level of private regulation in this market. (Hvelplund 2013, Hvelplund et al. 2007)

The interplay between the free market and the real market is often situated in the ideology, where the creation of a concept with arguments from both ideologies are used to limit and design the development. The strong and influential institutions are interested in the oligopoly real market to sustain and therefore use the ideology of a free market to argue against public regulation without moving their own private regulation of the market. When the economy is presented as an independent, objective and free market the strong stakeholders and the political institutions can design and develop a joint understanding of what is best for society. The statement of *"let the market decide"* as in neoclassical economy therefore rather become *"let us decide"* where the *us* are the strongest institutions and stakeholders in an oligopolistic market.(Hvelplund et al. 2007, Hvelpund & Arler 2015)

Creating a radical technological change in a system can, therefore, be difficult since the existing situation is lacking the will and empowerment towards a systemic change due to the neoclassical and concrete institutional approach. The necessity of establishing new institutions and empower new stakeholders in the market to achieve technological change can be addressed in the approach of innovative democracy. This approach aims to facilitate political goals based on a real democratic process where influence outside of the decision arena is enhanced. This aims to promote new institutions which are to break with the existing regime and create an opening for a technological change if it is necessary. Favouritism towards existing institutions and establishments are thus decreased or eliminated and new innovation are promoted through new institutions and stakeholders through the democratic process.(Hvelpund & Arler 2015) The innovative democracy approach, therefore, emphasise the importance of a change in organisation which is also outlined as a component in technology in section 3.3. Through changes in the organisational component can as such create new goals for society which can be imposed by indirect and or direct market policy. The success of the innovative democracy approach can, therefore, be said to exist when the effect of reforming of political processes establish alternative goals for society and hereby possibilities for radical technological change in existing markets and the institutional market condition (Hvelplund 2013). The participation and interaction between the political processes and various lobbyists are therefore levelling the playing field in between the importance of the lobbyists which secure equal competition and do not obstruct potential radical technological change.

The principal of the three different approaches to the market economy and institutions can be illustrated as in Figure 3.6 where a simplified understanding of the different approaches can impact politics and markets are presented.

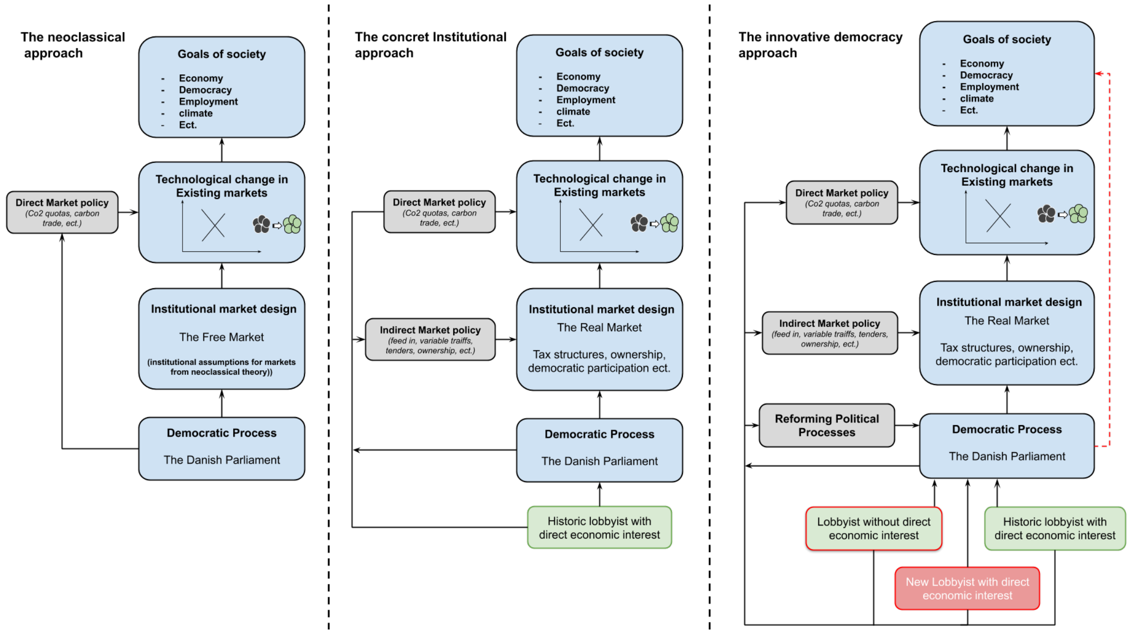


Figure 3.6: Own illustration of the three political economy paradigms (Hvelplund 2013, Hvelpund & Arler 2015, Mendonça et al. 2009) The change in technology happen in the existing markets and is this is presented in Figure 3.5.

The Figure 3.6 show the three aforementioned approach and their specification in relation to political economy paradigms and how impacts (grey boxes) can affect an overall system (blue boxes) which is based on democratic values. The impacts are similar in all the three approaches but as observed in Figure 3.6 only one is present in the neoclassical approach whereas two are present in the concrete institutional approach. This increase in impact occurs due to the additional inputs each approach provides to the understanding of the political economy paradigm. These new inputs are presented as coloured boxes for both the concrete institutional (green boxes) and the innovative democracy approach (red boxes). The input of *lobbies without direct economic interest* is presented as a green box with a red border, since it can be discussed if they are already introduced in the concrete institutional approach. However, this input is introduced in the innovative democracy approach where the emphasis on including lobbyist is essential while this also emphasising the technocratic dimension seen in the concrete institutional approach. The impact of reforming political processes aim to provide an opening for the input (red box and green box with red border) to participate in the democratic process. This can potentially change the goals of society (dotted red line) which then will restructure the existing markets and institutional market design.

The innovative democracy approach emphasises the importance of a change in organisation which also is outlined in section 3.3 if a new technology is to be implemented. Through changes in the organisational component affected the lobbyist, new goals for society can be developed and change society by indirect and or direct market policy.

The success of the innovative democracy approach can, therefore, be said to exist when the effect of reforming of political processes establish alternative goals for society and hereby possibilities for technological change in existing markets and the institutional market condition (Hvelplund 2013).

The understanding of this innovative democracy approach therefore becomes important for this report and outlines where change in the system can arise from. Consequently, the analyses need to consider this approach where a more comprehensive understanding of the effects of the development is considered in the economic calculations. Based on these assumptions and understandings the theoretical framework guide the report towards the relevant theories which can help to answer the research question.

Methodology 4

This chapter presents the methodology used in this report for answering the research question. The methodology combines the analysis, theories, data gathering and calculation methods and delineates how they are used to come up with a conclusion. This includes theories relevant to the stakeholder and energy system analysis and considerations on the validity of the conducted analysis. Overall, the methodology acts as a script on how the project is conducted.

4.1 Research Design

The methods presented as part of the research design are tools which are used to collect and create knowledge and are here presented together with the methodology applied in this report. The overall research design and the methodological approach in this report can be illustrated as in Figure 4.1 where the connections between the methods and the analyses conducted are presented.

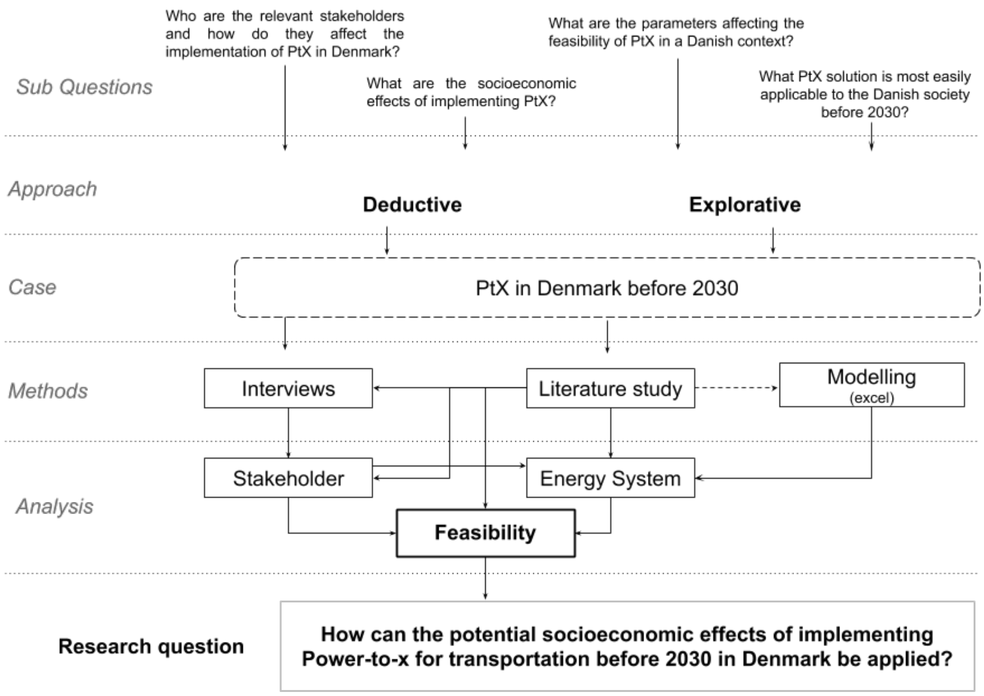


Figure 4.1: Own illustration of the research design with the methodology approach in the report. The mixed-methods approach can be observed as the arrows in *Methods* and *Analysis*.

The illustration in Figure 4.1 indicate how the research question is answered with help from the sub-questions which investigate four different characteristics of the research question. The research is conducted through an overall deductive and exploitative approach while the data are collected and utilised using a mixed-method approach. The mixed-method approach enables qualitative and quantitative data to complement each other, by that, contribute to a deeper understanding and validity of the report (Shorten & Smith 2017). The deductive approach is used to enable logical generalisations derived from the theory which is used in this report to understand basic definitions such as sustainable development, renewable energy and fundamental economic structures among others (Kennedy 2012). The exploratory approach is used to explore the research question with varying levels of depth (Brown 2006). This approach is applied in the energy system analysis in chapter 6, where it explores the effects of the different choices relevant for a certain PtX pathway in Denmark. The purpose of the exploratory approach is to investigate the problem with more flexibility and adaptability to change throughout the energy system analysis. The approaches are applied to the specific case; *PtX in Denmark before 2030* where the methods applied are interview, literature study and subsequently mathematical modelling of technical and economic aspects of a PtX pathway situated within the case. These methods are used to collect the data which are relevant for the analyses conducted in this report and due to the mixed-methods approach this data can complement each other. This is done through a stakeholder and energy system analyses that are conducted to clarify the socioeconomic effects of PtX in the transportation sector before 2030 in Denmark.

The Stakeholder analysis is therefore useful to map out the different stakeholders' relevance for the development of PtX in Denmark and show how they impact the investigated PtX solution. The Energy system analysis provides an understanding of the cost and resource usage of the investigated PtX solution compared to the current energy system. These analysis are used in an overall feasibility study of PtX in Denmark before 2030 and provide an understanding of how the framework conditions potentially have to change to enable the investigated PtX solution.

4.2 Data Collection

The data collection in this report is done through the mixed-method approach which enables qualitative and quantitative secondary data to complement each other. This contribute to a deeper understanding and validity of the report's results. (Shorten & Smith 2017) The main purpose of the mixed methods research approach can variate and can as a consequent be divided into five primary purposes for the approach:

- *Triangulation*
- *Complementarity*
- *Development*
- *Initiation*
- *Expansion*
  (Greene et al. 1989)

This report mainly utilises the *complementarity* purpose which seeks to elaborate and enhance results to provide meaningfulness and validity to the results (Greene et al. 1989). Through the mixed methods approach it is therefore possible to gain a better understanding of the connections or contradictions between qualitative and quantitative data gathered (Shorten & Smith 2017). The complementarity mixed-method approach is relevant for this specific report since the research question is multidimensional where various problems are entangled to each other. Combining the data therefore elaborates the understanding of these bonds and enhance the validity of the results. The data collected for this report are as such both qualitative and quantitative data gathered as primary and secondary data. The primary data are collected through interviews while the secondary data originate from literature reviews and document analysis.

SECONDARY DATA

The literature review and document analysis are used to identify already known information and data about PtX and the existing structures in the overarching policy and regulatory framework. These quantitative data are collected throughout the study and the process is therefore ongoing and the following items are analysed:

- Scientific papers
- Policy documents (global-, supranational- and national-level)
- News articles
- Datasets

These documents are used to gain a deeper knowledge of the PtX sector and to create the basis knowledge which is necessary to conduct the analyses. This includes the investigation of the case study, the PtX technology, yearly datasets for modelling, the stakeholders and relevant economic parameters. These inputs are all used to conduct the stakeholder analysis in chapter 5 and the energy system analysis in chapter 6.

PRIMARY DATA

The primary data consist of qualitative interviews which are performed to obtain knowledge from stakeholders which are relevant for the research question and the correlated sub-questions.

Interview

The interview as a method aims to obtain knowledge and can expand on how certain stakeholders actively work with or act toward a specific topic. Doing qualitative interviews with persons relevant to the research question can therefore help the interviewer to understand the methodology behind the stakeholder. The purpose of the interviews therefore is to attain a deeper understanding of the PtX sector in the Danish context and clarify the stakeholders relationship and attitude towards PtX.

The interviews are developed by inspiration from Kvale et al. (Kvale & Brinkmann 2009) where 7 essential elements for the framework to conduct an interview are mentioned to be: *Theme, Design, Interview, Transcription, Analysis, Verification and Reporting.*

Using this framework an interview guide for each interview is developed which help to structure and elaborate the research questions into actual questions for each specific interview (Kvale 2007). The interview guide, therefore, works as the main structure for the interviews which form are semi-structured. The questions in the interviews are structured as *open questions* which together with the semi-structured form allow asking more into detail during the interview and for the interviewed person to elaborate on specific topics (Kvale 2007).

The element of transcription is in this report neglected since the purpose behind the interview is to attain knowledge on the PtX sector and the stakeholders position and attitude towards PtX in a Danish context. The recorded interviews are used as background knowledge for the report and if quotes or statements are used directly in the report they are verified by the person making the statement. Each interview conducted is different why the specific reasoning and motive behind the interview and the conditions are outlined in the Table 4.1.

4.2.1 Validity of the interview

The interviews conducted as part of this report and the people interviewed, listed in Table 4.1, are important sources for the analyses in this report. Reflections upon the validity of the information provided are therefore important to address since the information affect the results in the report. It is therefore important to have a natural scepticism towards the information obtained and understand why and how certain persons could have a reason to promote certain beliefs or opinions. The interviews represent different stakeholer groups where *Ida Auken* represent the political entity and the parliament while *Jacob H. Zeuthen, Jan Tjeerd Boom* and *Morten Egestrand* from the DEA represent a part of the central administration. *Morten Stryg* represent the NGO entity while *Mads Friis Jensen* represent the Danish PtX industry. The interviewed stakeholders represent a small fraction of the complex reality but they represents a broad selection of relevant stakeholders for the stakeholder analysis, who also are able to provide useful knowledge for the energy system analysis. The interviews covered stakeholders from the *Regulator, Producers* and *NGO's* stakeholder groups which is presented in chapter 5. The information obtained through the interviews is compared to the literature and the researchers own knowledge to determine if the information can be seen as valid for the analyses. An essential part of this is to recognise how the stakeholders participate in the PtX development and if the stakeholders have an economic interest in PtX. This comparison to the literature is especially relevant to increase the validity of the technical information provided in the interviews to address the adequateness and estimate if the data can be used in the report. If the data can not be compared to the literature these are understood as highly uncertain and used with care in the report. The mixed method approach is therefore valuable and helps the researches to validate the information used in the report and fill potential gaps from the literature in regards to technical data.

Most of the interviews were conducted online through the *Skype* application or the phone, with the exception of two face-to-face interviews. The interviews which were not face-to-face were more difficult to conduct since there are natural limitations linked to these type of interviews. Asking follow-up question based on the reactions of the interviewee or using illustrations to explain questions or answers are as such not possible. However, the online and phone interviews enabled the interviewers to be more efficient since travel time is eliminated which can be a limitation in the selection of the interviewees.

The *Briefing* prior to the interviews was also reduced since the email correspondence for setting up the interview often included presenting a lot of the information from the briefing. The actual briefing was therefore often reduced to be the information from the briefing that had not been addressed before the meeting. The interviews were recorded to distribute the knowledge in the research group and to make it possible to consult the information from the interviews throughout the entire research process. Prior to the submission of the report, the statements or citations from the interviews were sent to the relevant interviewee to verify and approve the statements or citations linked to them presented in the report. The statement from *Ida Auken* has nevertheless not been verified since she withdrew from the position as chairman from the *climate, energy and utility committee* due to health issues. The statement is nevertheless deemed to be generic why it still is used without the verification and approval from *Ida Auken*. From a methodological point of view, the statement should however be seen as highly uncertain due to the lack of verification. The interview with *Johannes Peschko* and *Ida Auken* furthermore did not follow the strict structure of the interview guide, why only a short presentation with an emphasis on the *purpose of the interview* and *recording/citing* was presented prior to the interview. This was done due to time issues in the case of *Ida Auken* and due to a prior professional relationship to *Johannes Peschko* why the interview was less formal.

Ida Auken	Chairman of *The Climate, Energy and Utilities Committee in the Danish Parliament. Radiale Venstre* The specific info of the interview can be seen in appendix C in table C.2 The interview was conducted face-to-face and used to understand how the *The Climate, Energy and Utilities Committee in the Danish Parliament* works with and address PtX in the political framework. The statement used from this interview in the stakeholder analysis is not verified by the interviewee.
Jacob H. Zeuthen	*Chief Advisor at the Danish Energy Agency Centre for Systems Analysis.* The specific info of the interview can be seen in appendix C in table C.3 The interview was conducted over the phone and additional question was answered through e-mail correspondence. The purpose from this interview was mainly to clarify uncertainties related to the *teknologikatalog* and additionally provide insight into the *DEA's* work with PtX from the technological perspective. The statement used in the report from this interview is verified by interviewee.
Jan Tjeerd Boom	*Chief Advisor at Centre for Systems Analysis at Danish Energy Agency* The specific info of the interview can be seen in appendix C in table C.4 The interview was conducted online and the purpose of the interview were to get an insight into how the *DEA* works with socioeconomic evaluations. This provided valuable knowledge on how to treat specific economic parameters in the feasibility study and provide insights into how the *DEA* work with PtX in a socioeconomic perspective. There are no statements from the interviewee used in the report.
Johannes Peschko	Managing Director at *Ride Capital Consulting GmbH* The specific info of the interview can be seen in appendix C in table C.5 The interview with Johannes Peschko was conducted over the phone and regarded the usage of excess heat in a biogas plant. The interviewee is a project manager of the current PtX project named; *BioCat Roslev.* The statement used in the report from this interview is verified by interviewee.
Mads Friis Jensen	Co-founder and CCO at *Blue World Technologies* The specific info of the interview can be seen in appendix C in table C.6 The interview was conducted over the phone and additional question was answered through e-mail correspondence. The purpose from this interview was mainly to clarify uncertainties related technology and financial data relevant for the energy system analysis. The statements used in the report from this interview is verified by interviewee.
Morten Egestrand	Advisor at Center for System Analysis, Energy Efficiency and Global Cooperation at *Danish Energy Agency* The specific info of the interview can be seen in appendix C in table C.7 The interview was conducted online and the purpose of the interview was to clarify how the DEA work with PtX at at the national level in the Danish energy system. The statements used in the report from this interview is verified by interviewee.
Morten Stryg	*Senior Consultant at Danish Energy* The specific info of the interview can be seen in appendix C in table C.8 The interview was conducted face-to-face and the purpose of the interview was to clarify how an NGO work with PtX and generate background knowledge of PtX in the Danish context. There are no statements from the interviewee used in the report.

Table 4.1: Presentation of the people interviewed as part of writing the report.

4.3 Overall Analytical Approach

The report's main objective is to investigate a pathway of implementing the socioeconomic impact of implementing PtX in the Danish energy system before 2030, which as such undergoes a technological change. To investigate this a feasibility study is conducted which is assisted by a stakeholder analysis and an energy system analysis. The stakeholder analysis can outline the relevant stakeholders for developing PtX in a Danish context and outline how these potentially can affect the future development. The energy system analysis investigates the deployment of a PtX plant before 2030 from both a technical and economic perspective with a focus on overall CO_2 reductions in the operation plan. The technological pathway for the plant is chosen based on the TRL of the PtX solution and the ability of the output from the plant to displace fossil fuels in the transportation sector. The analytical approach furthermore commences the groundwork of presenting and describing the theories which all are part of the theoretical framework presented in chapter 3, explaining the framework conditions in which the research question is situated.

4.3.1 Feasibility Study Theory and Approach

The analysis in this report is based on the theory on *Feasibility Studies* by Hvelplund and Lund (Hvelplund & Lund 1998) where the theory of the study is presented. The purpose of a feasibility study is to investigate how feasible a certain solution is to a given problem considering both business and socioeconomic measures in the present context. This can especially be relevant when the solution endure a radical technological change since the study can be designed for a feasible technical alternative where including and evaluating both the social, environmental and economic effects of the alternative is important. This can help to identify more desirable alternatives which are not automatically being implemented under present market conditions.

The feasibility study can be scoped as either a socioeconomic feasibility study, where the solution is correlated with feasibility for the society as a whole or a business feasibility study, which determines if a solution is feasible for a specific company. Determining from which point of view and why the feasibility study is made is therefore important. When doing the feasibility study it is furthermore important to relate it to the specific historical context and to understand the infrastructure and organisations where a solution is analysed to discuss solutions on a long-term basis. The study, therefore, has the potential of becoming a link between short- and long-term effects of the alternative investigated which can help to find an adequate transition pathway between the existing technologies and the necessary future technologies. The necessity of integrating the near future with the long-term perspective should as such be emphasised since this can outline the potential in a technological change and then expose the necessary changes in legislation to facilitate the change. This can be illustrated as in Figure 4.2 where a capital intensive technology with a long technical lifetime that is more desirable for society as a whole, requires a change in the market rules to be competitive compared to existing technologies. (Hvelplund & Lund 1998)

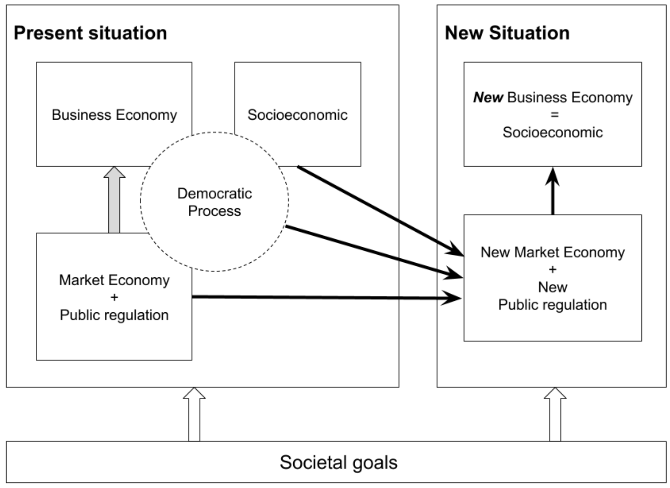


Figure 4.2: Own illustration based on Hvelplund et. al (Hvelplund & Lund 1998) which show how the democratic process can link the present conditions (market economy + public regulation) business economy studies and socioeconomic studies to create new public regulation where socioeconomic value is embedded in business economic study.

The feasibility study can, therefore, consist of both business economy and socioeconomic parameters and is a mean to change the market rules through a democratic discussion, to level the playing field for new technologies against present technologies. The feasibility study can be performed from a business economy or socioeconomics point of view which include different factors. In broad terms, business economy studies are usually done by companies who are considering investing in a project, while socioeconomic analysis are often done by governmental entities and NGOs. Socioeconomic differs from business economics because it has society's interests at its centre. Table 4.2 compares the differences between socioeconomics and business economics regarding feasibility studies. Here the total interest rate is updated to the current recommendation of the Danish Ministry of Finance of 4% (Ministry of Finance 2018) instead of 7% which is suggested in (Hvelplund & Lund 1998).

Considerations	**Socioeconomic**	**Business Economics**
Costs and prices	Exclusive taxes on goods and services	Inclusive all taxes
Future prices	Estimates from the Ministry*	Estimates from private sector
Interest calculation-rate	Total interest rate of 4% p.a.	Market interest rates
Environmental costs	Included	Normally not included.
Employment effects	Considerations are included	Normally not included
Importation effects	Considerations are included	Normally not included

Table 4.2: Own presentation of the different factors and assumptions considered for socioeconomic and business economics analysis based on Hvelplund et al. (Hvelplund & Lund 1998)*Ministry of Climate, Utility and Energy

Through a combination of business- and socioeconomic studies the typical favouritism of existing technologies in the present system conditions can be decimated, and the development of new technologies that benefit society as a whole can be examined and discussed. This happens through the aforementioned democratic discussions which eventually can lead to new regulations and market rules which benefit society as a whole. Consequently, this creates a new situation where the new business economy study includes the parameters from the socioeconomic studies. (Hvelplund & Lund 1998)

In this report, the feasibility study investigates how a specific implementation of PtX in the Danish energy before 2030 affects the danish society from a socioeconomic point of view. The feasibility study is relevant since the theory emphasised the importance of not only conducting business economic analysis when the profitability of an energy system needs to be estimated but also to include socioeconomic parameters. Additionally to the business economics of the system, the "hidden" profits have to be considered, here meant the overall effects on an energy system situated in a society with visions and goals for this society.

If a business economy analysis and a socioeconomic analysis are compared it is often observed that these are conflicting when it comes to who benefits from the solution. This indicates that public regulation should influence the business economy to make it resemble the socioeconomic parameters and benefit society as a whole. The feasibility study includes all of these aspects and can be used to influence the presents regulation towards a new situation and can be illustrated as in Figure 4.3.

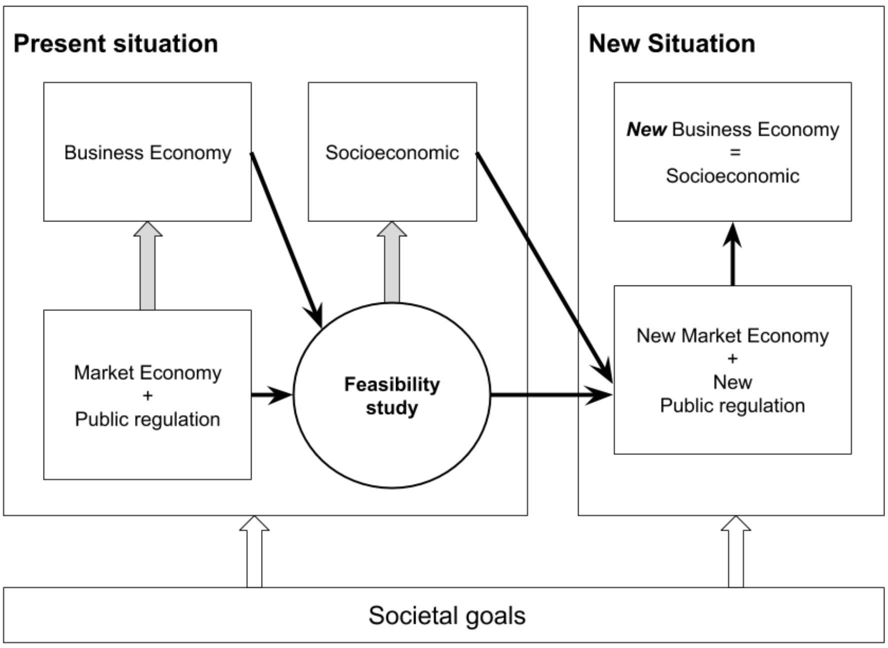


Figure 4.3: Own illustration of the the interrelation between business economy, public regulation, market economy and socio-economy. Emphasising the importance of the feasibility study to enable what is best for society and not favour existing technologies. (Hvelplund & Lund 1998)

It is seen from Figure 4.3 that the business economy is influenced by the market economy and the current public regulation. Depending on the economic paradigm the market economy can affect the business economy in different ways, which is elaborated in the section concerning Market Economy and Institutions in chapter 3. The public regulation can influence the business economy either through subsidies or laws. As previously mentioned, the feasibility study is encouraged to investigate the socioeconomic aspects of a system and not only the business economy. If a case is good for society but not good for business it should be discussed in the democratic arena, which can potentially lead to new public regulation enabling the case. The feasibility study can therefore be a mean to comprehend the socioeconomic value in combination with the business economic value to create an ideal new situation favouring society. This can be done with inputs from the choice awareness theory which can help to promote this alternative route for society. The technology utilised in this report can furthermore be considered as a radical technological change why considerations related to the deployment of this change have to be addressed.

4.3.2 Stakeholder Theory and Approach

The stakeholder analysis aims to identify the relevant stakeholders who are involved and affecting the development of the PtX in Denmark. Stakeholders can be both individuals, groups and organisations rooted in both the private and governmental sector. All the different stakeholders take part in the process of the development of PtX and therefore have the attributes to affect the future development directly or indirectly. Depending on the decisions taken, the future stakeholders can either be affected positively or negatively why an analysis of the stakeholders different stake versus their influence can provide knowledge of risks and gains. (Kørnov 2007) Understanding the stakeholder scene can therefore help to clarify coalitions, interrelationships and how this affects the future development of PtX in Denmark and can be mapped as in Figure 4.4.

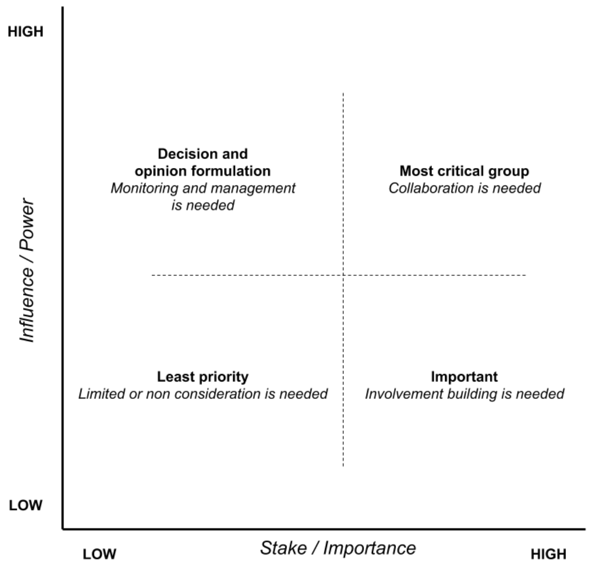


Figure 4.4: Own illustration of the classifications of stakeholders defined by importance or power and influence or stake. (Chevalier 2001, Overseas Development Administration 1995).

Mapping the stakeholders as in Figure 4.4 provides useful insight into their importance and power in the decision-making process. Since the research question in this report is investigating a specific development pathway towards 2030, the stakeholder overview and later analysis ,therefore, provides insight into from where barriers and opportunities can arise. The stakeholder analysis is furthermore conducted within the overarching theoretical framework, which is presented in chapter 3, which provide a deeper understanding of the adequate macro- and micro-structures where the stakeholders are situated.

4.3.3 Energy System Analysis Approach

Analysing a PtX solution before 2030 in the current danish framework is done through mathematical modelling which has been described by Neumann as:

> *"By a model is meant a mathematical construct which, with the addition of certain verbal interpretations, describes observed phenomena. The justification of such a mathematical construct is solely and precisely that it is expected to work — that is, correctly to describe phenomena from a reasonably wide area."*
> (Neumann 1961, Page. 492)

In the present report, a mathematical model is used to simulate some aspects of a real PtX plant. The physics, the intrinsic logic and most of the calculation methods of the model are handled by the modelling tool. On the other hand, plant design, capacities and economics among others are defined by the user. To build the model, different inputs are required that can be, for example, market data on current prices, projections for future prices, assumptions for the future development of taxes and regulations. The model is built to construct a representation of a PtX plant in which the operation is optimized hourly to maximize the yearly socioeconomic value. Given that some of the inputs to the models are assumptions or projections, there can be a high degree of uncertainty in some of the inputs. Therefore, it is a good practice to run a sensitivity analysis on the most uncertain inputs to test the robustness of the results to inputs variations.

Modelling Environments

One of the objectives of the model is to be able to find a suitable operation mode to increase the socioeconomic value that PtX can provide to the Danish society. The technical requirements outlined in section 3.2 for energy systems with a high share of RES requires a flexible modelling tool. Microsoft Excel was the tool chosen because it provides a high degree of flexibility and control over the calculation methods and formulas used. However, solving complex problems that involve hourly optimisation and storage managing can be a challenge and involve using advanced features such as Visual Basic scripts. However, Excel is a great tool to conduct economic evaluations due to the built formulas and the spreadsheet layout which makes it easy to calculate it for different years. Even though Excel is the main modelling tool, EnergyPRO was used to extract the wind speed hourly profile that was used in the analysis using the calculation method described in Appendix D.

The analysis consists of various scenarios tested with a PtX plant scaling optimised to best fit the scenarios. The variables controlling the plant scaling and limiting the production are presented and discussed when the finished model is presented, in chapter 6. Since the plant analysis is to be conducted in this manner, the environment has to make the various sizes and capacities of the plant and connected storage's dependent on the availability of renewable resources which is addressed, in section 4.3.3. This variation of capacities and sizes are automated in Excel, why this is the prime environment in which the analysis is be conducted. Additionally, this environment provides flexibility and a large degree of freedom and control over the model which is needed for the energy system analysis in this report. In addition, it is also possible to obtain index values from other modelling environments such as EnergyPRO. The data can be downloaded and inserted into the main modelling environment to assist in the analysis.

The PtX plant relies on available CO_2 sources which are outlined to be an important factor that primarily can limit the possible capacity size of the plant. (Danish Energy Agency 2017) The mapping tool created by AAU on biogas methanation sources in Denmark was as a consequence utilised to determine the possibilities of capacity for the methanol plant in the Danish context. (Sustainable Energy Planning Department, AAU 2020) This tool have an index containing the available CO_2 sources from *Agricultural*, *Waste Water Treatment*, *Waste Disposal sites*, *Industrial* and *Other* sources. This mapping tool outline available CO_2 sources from a set of pre-made criteria. These criteria include *Type of source*, *Placement*, both municipal and regional, *Proximity to needed infrastructure* both gas, heat and electricity grid, *Gas injection upgrade* and *Electrolyser capacity size*. Here the main used criteria is the capacity electrolyser. Despite this tool is used to estimate the available CO_2 source for power-to-methane, the methodology behind the tool enables it to be directly transferable for power-to-methanol since their CO_2 requirements are similar. Because of this, it is assumed that from the estimation of the adequate capacity used for the plant, the mapping tool can provide information on the possible quantity of plants able to be created in Denmark. This quantity is then used to provide the needed information to discuss the possibilities of a large scale implementation of PtX in Denmark using the analysis of a single plant scaled up. Based on the plant modelled in this report the possible CO_2 sources was furthermore outlined by using the mapping tool *Qgis*. The map created through *Qgis* shows the potential source sites was furthermore merged with the Danish DSO tariffs for the different DSO areas to show how this input affects the potential plants differently. The use of *Qgis* in this report is minimal why the method is not further addressed in the report.

Economic Calculations

Excel is used for modelling the technical aspect of the plant including minor optimisations and evaluate the economy of the designed plant. The economical evaluation is conducted with a socioeconomic focus, to follow the main research question of this project. As presented in Table 4.2 on page 37, additional elements to a business economic analysis such as environmental costs, employment effects etc. needs to be considered.Additionally, the employment and importation effects are considered by a rough estimate and presented separately from the main economic estimation.

The feasibility of investment to the plant is estimated over its entire lifetime, and not be limited to provide a profit within a few years as often seen when conducting a business economic analysis of a plant.

The economic evaluation of the PtX plant considers the yearly operation and maintenance and electricity costs. The cost of retrofitting cars is furthermore added to the total investment of the plant for the relevant scenario. The income consists of socioeconomic gains and the income from methanol sales. Since the methanol is used to replace petrol, the price of methanol is based on that of petrol, taking energy content and engine efficiency into account. An example of how the lifetime NPV calculation of the plant could look is shown in Figure 4.5.

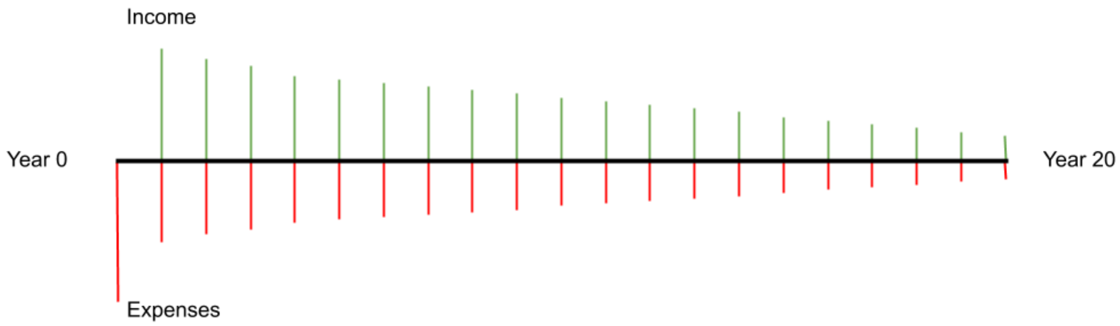


Figure 4.5: Own illustration of the economic calculation used for the analysis. It should be noted the the income and expenses are not scaled, but merely used for illustrative purposes.

It is seen in Figure 4.5 that the income and expenses are declining as the years go by, this is due to the value being estimated in year zero. The actual value within the year of production is therefore brought back to year zero by doing a net present value (NPV) estimation. The formula for calculating the NPV is shown below:

$$NPV = \sum_{i=1}^{n} \frac{Values_i}{(1+rate)^i} \tag{4.1}$$

Where:

- i is the year number
- n is the maximum amount of years, in Figure 4.5, this would correspond to 20
- $Values$ is the value of income subtracted by the expenses for the year i is the year number
- $rate$ is the discount rate

The discount rate defines how the future value of an investment is to be understood at the time of investment as the present value. Depending on what discount rate is used either more or less value is assigned to the beginning or the end of the investment. A high discount rate would therefore assign more value to early income or expenses while a low discount rate assign more value to later income or expenses. In the calculation of the NPV the discount rate is therefore and important aspect to consider.

In addition to the NPV, the IRR (internal rate of return) is also used to present some of the results throughout the report. The IRR can be defined as the interest rate that makes the NPV be zero. In one way, using the IRR makes it easier to see if the project's operations would pay for itself without considering any interest rate. If the IRR is above 0 %, it means that the project would pay for itself if no interest rate was considered. The IRR is also a good indicator because it is a simple way of presenting how much return a project gives independent on how much the investment is. In that sense, it is easier to compare projects with different investment costs.

As mentioned, the expenses consist of operation and material cost plus engine replacement and the initial cost of construction, whereas the income consist of the socioeconomic values of producing and selling electrofuels. Here the electrofuels produced are be given the value of their fossil fuels counterparts. This price estimate is made accounting for the engine efficiency and energy density of the fuels.

For the energy density, it is assumed that the consumers are willing to pay the same price for travelled distance. As such, the proposed methanol costs would correspond to the gasoline costs. The gasoline price used is approximately 0.62 €/L corresponding to fuel cost and surcharge in 2019 (Winther 2019). Using an energy density for gasoline of 32 MJ/L, the gasoline price in € / L can be divided by the energy density, resulting in a cost of 0.02 €/MJ. This cost represents the applied cost for methanol. Compared to the current market price of methanol of 0.01 €/MJ (Methanol Institute 2020), the used price is approximately twice as high. However, the electricity-based methanol is replacing gasoline and not fossil methanol. Therefore, the revenues are calculated based on the price of 0.02 €/MJ. This relies on the assumption that consumers are willing to pay the same for fuels.

The concept of electrofuels is relatively new, why no minimum requirements have been decided when it comes to the greenhouse gas emissions created as a consequence of using electrofuels. In this project the methodology used for defining biofuels (European Union 2018, article 29) was applied to the electrofuel product to determine the sustainability of the production methods. The methodology behind determining the minimum CO_2 savings, and the applied value used for this project, is presented in the following section.

CO_2 Savings

The purpose of developing electrofuels is to reduce the overall CO_2 emissions in the Danish transportation sector, consequently helping Denmark towards a net zero-emission society in 2050. Whether or not the produced electrofuels can be considered sustainable or renewable depends on; *how the carbon is sourced and how the hydrogen and subsequently the electrofuels are produced.* In this report, the CO_2 source is assumed to be sourced by the CO_2 emissions originated by biogas upgrading which only use biomass such as slurry, agricultural residues and biogenic waste why the carbon source is considered to be of renewable origin and therefore carbon neutral.

When developing a methodology to determine the sustainability of electrofuels used for transportation, RED II supplies a method of greenhouse gas determination, used for defining the criteria for biofuels and bioliquids.

The RED II set a few criteria in *article 29* in regards to the agricultural-based products and their originating area (European Union 2018, article 29). The following article in the RED II, *article 30* furthermore address the verification of compliance with the sustainability and GHG emission saving criteria (European Union 2018, article 30). The criteria mentioned in the RED II are all relevant and in this project assumed to ensure and document the sustainability of electrofuel production. Article 19 in RED II furthermore mentions the Guarantees of Origin (GO) scheme which aim is to quantify and demonstrate the renewable energy towards the final consumer for both electricity, gas/hydrogen and heating or cooling (European Union 2018, article 19). However, there is no GO's scheme specific for electrofuels while the EU project, Certify, while aim to generate a framework for GO's for green hydrogen, is still not deployed in an EU wide context. The Certify project works with two types of GO's. One is for green hydrogen made from RES and one for low carbon hydrogen which refers to hydrogen with at least 60% reduction in CO_2 emissions compared to a fossil reference. (CertifHy 2020)

Based on this framework and considerations at the EU level, this report adopts the methodology used by The International Sustainability and Carbon Certification (ISCC) to calculate the CO_2 avoided by using electrofuels. The methodology is used to make sure that the produced electrofuel can be categorised as a biofuel, which together with bioliquids are required to achieve a GHG emission saving of at least 60% compared to fossil references to be considered sustainable. These emission savings are also including upstream emissions such as extraction, distribution, ect. (ISCC 2016) The total GHG emission is thus calculated based on the formula:

$$E = e_{ec} + e_l + e_p + e_{td} + e_u - e_{sca} - e_{ccs} - e_{ccr} - e_{ee} \tag{4.2}$$

Where:

- E total emissions from use of the fuel,
- e_{ec} emissions from the extraction or cultivation of materials,
- e_l annualised emissions from carbon stock changes caused by land use change,
- e_p emissions for processing,
- e_{td} emissions from transport and distribution,
- e_u emissions from the fuel in use,
- e_{sca} emission saving saving from the soil carbon accumulation via improved agricultural management,
- e_{ccs} emission saving from carbon capture and geological storage,
- e_{ccr} emission saving from carbon capture and replacement, and
- e_{ee} emission saving from excess electricity from cogeneration
  (ISCC 2016)

Since equation 4.2 is designed to estimate the GHG emissions of biofuels and bioliqueds, various elements of the equation is not applicable when estimating the GHG emissions of electrofuels.The equation can thus be derived to:

$$E = e_{ec} + e_p + e_{td} + e_u - e_{ccr} - e_{ee} \tag{4.3}$$

The elements of equation 4.2 concerning land use, and geological storage are removed in equation 4.3. Furthermore, the emission savings from excess electricity from co-generation is disregarded from the GHG calculation in this report. This is done since the electricity market is treated as a whole, meaning that an hourly profile for the electricity price and GHG emissions is used for estimating the processing and extraction emissions, instead of dividing it into the various electricity-producing units and measuring the emissions from each of these. This is done to make the estimated plant in this report more applicable to the whole of Denmark, and not just one region. A consequence of this is that the electrofuels produced in the plant, in reality, could have a lower amount of GHG emissions than presented in this report. Additionally, it is assumed that the electrofuels investigated can be distributed in the same manner as their fossil counterparts, and the emissions created by this distribution are therefore assumed to be negligible. The final equation for calculating the GHG emissions of the fuels in this report is therefore:

$$E = e_{ec} + e_p + e_u - e_{ccr} \tag{4.4}$$

When applying equation 4.4 to the petrol, to which the electrofuels are compared, it is seen that for petrol these numbers are 26 g CO_2 pr. km for production and 169 g CO_2 pr. km for petrol in use. This is for vehicles driven for 220 000 km. Here the production includes extraction and processing of the fuel. (European Environment Agency 2017)

This give a total GHG emission of 195 g/km for petrol. The relevant properties for the petrol are shown in is the table below:

Petrol		
Engine efficiency	0.20	
CO_2 exhaust	2.31	kg/liter
Energy density	9.67	kWh pr. liter
Density	0.75	g pr. liter

Table 4.3: Values for petrol and petrol driven vehicles. The combustion engine efficiency was obtained from (Danish Energy Agency 2020*a*) for 2020.

While methanol fuel-cell-powered vehicles have the potential of replacing diesel-powered vehicles, this report only focuses on methanol for replacing petrol. This is mainly due to its potential of gradually replacing petrol by mixing it in various mixing ratios as discussed at the end of section 1.4. From the values of CO_2 pr. km and from the values presented in the table 4.3 the CO_2 pr. kWh is calculated to be 1.194 kg for petrol, for the fuel in use. For producing petrol the European Environment Agency (European Environment Agency 2017) suggest that the GHG emission is 0.184 kg CO_2 pr. kWh. Using equation 4.4 this gives a total of:

- Petrol = 1.378 kg CO_2 pr. kWh

For the produced electrofuel to live up to the same standards as biofuels this would mean that their GHG emissions would have to be 60% reduced compared to their fossil fuel counterpart, meaning that if the electrofuel should replace petrol its production and usage emissions should be less than 0.551 kg pr. kWh.

The efficiency of the electrofuel powered vehicles is dependent on which type of technology is used. One of the major advantages of power-to-methanol is that it can be used by common vehicles by mixing it to gasoline up to 15%v/v (EU countries already have 3-5%) (Methanol Institute 2016) and by flex vehicles up to 85% (Danish Energy Agency 2017). Thus, increasing the methanol share in the gasoline will not require additional investments for the consumers, meaning that an increase in methanol production can be handled by the current transport system without major changes. In addition, methanol being in liquid form means it does not require additional electricity consumption for compression to be stored. Naturally, producing methanol using renewable electricity can help to displace fossil fuels in the transportation sector. The major disadvantage of the process is that the overall energy conversion efficiency is low if compared to the electrification of vehicles, which needs to be taken into account when doing a GHG emission estimation of methanol production and usage. For producing methanol the Danish Energy Agency (DEA) (Danish Energy Agency 2017) presents that a power-to-methanol plant operates at an efficiency of 0.58. The GHG emissions from water use for the electrolysis are not considered in this report, but should also be considered in further evaluation of the emissions as a result of methanol production. For this project, the CO_2 used to produce the methanol is taken from an already emitting CO_2 source. The CO_2 source is therefore considered neutral since it is already occurring. The only emission source from the methanol is the source of the electricity why the CO_2 content of the electricity is the limiting factor when producing electrofuels if they are to live up to biofuel standards. Table 4.4 contains the efficiency of end to end use of various applications of methanol along with the corresponding CO_2 limit to the electricity.

	Mixed with petrol (15%)	M85 (85%)	Fuel cell (100%)
Engine efficiency	0.20	0.20	0.40
CO_2 limit	63.92 g	63.92 g	127.83 g

Table 4.4: Efficiencies for varies applications of methanol in vehicles and the corresponding limit of CO_2 content in the electricity used for production.(Nagamoto 2001)

The values presented in Table 4.4 does however not account for the efficiencies of additional equipment for the methanol plant, such as additional hydrogen storage and the corresponding compressor requirements. These are presented and implemented to the production pattern when conducting the energy system analysis in Chapter 6. As seen in Table 4.4, the applications with methanol petrol mixes have a lower efficiency than those using methanol in a fuel cell. This is due to the mixed applications being used in compression engines which in general have a lower efficiency than fuel cells.

In this report, the potential of PtX as a product is to be investigated, why the most scenarios are using fuel cells for methanol usage. Using fuel-cells does however also require additional investment into the retrofitting existing vehicles from using petrol in a combustion engine to be using methanol in the current context unless brand new methanol fuel cell cars are introduced to the system. It is most likely in the short term that retrofitting existing vehicles is the feasible option which results in an added investment cost. This added investment is viewed as a societal cost, and is therefore included in the economic analysis of the plant. Additionally, the application of a methanol mix with petrol, along with the corresponding CO_2 content limitation of the electricity is investigated in another scenario. In this scenario, the production hours of the plant are as such be limited, but the investment price solely covers the plant construction and materials, and not the investment of retrofitting petrol vehicles. This enables the results to be used for a broader evaluation of PtX in Denmark. The production pattern of the plant is therefore influenced by the engine efficiency and the CO_2 content in the electricity grid as presented in table 4.4 which therefore provides a production pattern displayed as the *Average Method* in table 4.5. The CO_2 content of the electricity consumed is obtained from the Danish TSO's dataset on CO_2 emission per hour for electricity delivered to the distribution grid (Energinet 2020*a*). The average value of the CO_2 content has the average value of import included and it is weighted against consumption, which gives the CO_2 emissions per used KWh in Denmark. This value is correlated to the price zone investigate which is DK West (DK1) and the selected CO_2 emissions per consumed KWh is using the 125% method, meaning that the emission rate from the CO_2 assign co-produced heat is produced by a given efficiency by 125%.

In table 4.5 two methods of applying the CO_2 limitation are shown. The checkmarks show whether producing is possible or not. The first one called *Marginal Method* where the CO_2 content for each hour needs to be lower than the maximum allowed, the second method called *Average Method* where the estimated total average of all hours needs to be lower than the maximum allowed CO_2 content. As seen in the picture the production using the *Marginal Method*, is limited in its production hours, compared to the *Average Method*. The average CO_2 content of the electricity does however become unnecessary low for the *Marginal Method*, whereas, for the *Average Method* it is still within the allowed limits while operating at a lot more hours. Since the *Average Method* allows for more production hours while still reducing the average CO_2 emission to a degree that lives up to the requirements for biofuels, this method is chosen for the analysis. This could lead to issues of GHG reduction verification, but for the purpose of this report, this method is deemed sufficient.

Hour	CO_2 **(g/KWh)**	**Marginal Method**	**Average Method**
1	39.66	✓	✓
2	62.86	✓	✓
3	69.52	✓	✓
4	55.82	✓	✓
5	57.62	✓	✓
6	51.42	✓	✓
7	74.66	✓	✓
8	93.30	✓	✓
9	125.29	X	✓
10	155.98	X	✓
11	155.84	X	✓
12	136.11	X	✓
13	116.67	X	✓
14	117.42	X	✓
15	125.21	X	✓
16	135.86	X	✓
17	132.95	X	✓
18	135.73	X	✓
19	155.62	X	✓
20	162.54	X	✓
21	179.45	X	X
22	147.27	X	✓
23	144.86	X	✓
24	117.56	X	✓
Average CO_2	114.55	63.10	111.73

Table 4.5: Comparison between the marginal and the average methods for defining whether or not a certain hour meets the CO_2 criterion. The presented data is for the 14^{th} of January 2019 in price area DK West.

Scenarios

The energy system analysis is performed via scenarios where certain aspects, regarding the chosen pathway for the PtX solution, is investigated. The purpose of the scenarios is to develop and clarify how these aspects impact the PtX solution utilised in the analysis. The concept of scenarios can be described as:

> *"Scenarios are "what if" stories about the future, expressed in words, numbers, maps, and/or graphics. They are descriptions of plausible futures and do not claim to offer any certainty about future developments because uncertainty is assumed to be inherent in a complex world." (Pizzol 2017, page 2)*

The scenarios developed in this report are created for the same PtX pathway but investigates different parameters effects on the outcome. Modelling different scenarios create different results, show how certain aspects can change the output of the energy system analysis, and consequently the overall feasibility of the investigated PtX solution. However, it is important to notice that the scenarios are not able to comprehend every aspect of reality. The scenarios are replications of reality set in the theoretical framework outlined in the report. In this project the pathway for PtX is chosen to be the production of methanol which is utilised through four different scenarios:

- *Offsite*; where the electricity used for the plant is imported from the electricity grid, therefore having a CO_2 content as that of the grid while grid tariffs also are included.
- *Onsite*; where a capacity of wind energy is added to the plant. This reduces the CO_2 content of the used electricity and also excludes tariffs whenever the wind-turbines produces electricity for production.
- *M15*. Identical with *Onsite*, but the methanol is used in a petrol mix as drop in, excluding investment into retrofitting existing petrol vehicles, but also increasing the requirement for lowered CO_2 content in the used electricity.
- *Onsite +*. Identical with *Onsite*, but with an assumption that all excess heat and oxygen produced can be sold adding further revenue to the business case. The cost of retrofitting existing petrol vehicles are furthermore ranged as the mean of the estimated price range for this, why it is two-thirds of that used in the *Onsite* and *Offsite* scenarios.

The scenarios are presented and the most suitable scenario, to provide some general considerations towards PtX in a Danish context, is selected and used to investigate various parameters in a sensitivity analysis.

Sensitivity Analysis

A sensitivity analysis is used to test the robustness of a technology, plant or energy system. The robustness of the plant shows its ability to handle changes to the settings in which it operates. This can be done from various methods and this report use the *local* method which explores the reduced space of the input factors around the model. (Tian 2013)

The changes investigated through the sensitivity analysis indicate whether the build scenario results are applicable in a broader sense than simply to the first defined specific situation.

Socioeconomic Effects

Given that this report investigates the socioeconomic potential of PtX, the considerations as presented in table 4.2 on page 37 are to be estimated. For some of these, an exact value cannot be applied to the analysis. An example of this is the employment effects, where the creation of jobs in the PtX industry create new jobs adding to the socioeconomic value, while it also eliminates already existing jobs within the fossil fuel industry, which would create a loss in socioeconomic value.

The methodology used to calculate the employment effects follows the one used in the Ida's Energy Vision 2050 (Mathiesen et al. 2015). Firstly, an estimation of the domestic share of turnover is done, by calculating the shares of the investment and costs that stay within Denmark. The added domestic turnover is then assumed to be used for job creation within the country. Assuming 1 million euros per year is equal to 15 jobs, the number of jobs created can be estimated.

However, there is some uncertainty regarding this analysis because the possible jobs lost in the fossil fuel industry are not accounted for. The results of the job creation analysis are not used directly in the NPV calculations but are presented as a side result.

Another element of the socioeconomic elements to be considered is the environmental cost. Here the methanol usage provides an overall saving of CO_2 due to the decreased use of fossil fuels in the transportation sector. The CO_2 avoidance income of this is tested in a range from the 25 €/ton which is the approximate European CO_2 quota price in 2019 (Danish Energy Agency 2018*a*), to a price of 200 €/ton as suggested by The Danish Climate Council to reach the 2030 emission reduction goals (Klimarådet 2020*b*). For the tested scenarios, a price of 74 euro pr. ton is used. This value represents a high cost of the estimated social value of mitigating action in 2020, by the Carbon Pricing Leadership Coalition (Carbon Pricing Leadership Coalition 2017). The social value of mitigating action is defined to be the:

> *"[..] the economic and environmental value of voluntary mitigation actions and their co-benefits for adaptation, health, and sustainable development."*
> (Carbon Pricing Leadership Coalition 2017, page. 53)

This social value includes immediate benefits such as energy security, health improvement and effects on agricultural productivity and long term development benefits of adjusting productivity towards a carbon low productivity. (Carbon Pricing Leadership Coalition 2017) The actual value of this was presented to be between 37-74 € but it is foreseen to increase by 2030 to between 46-92 €. In this project, it is assumed that this price will continue to increase past 2030, and since the social value of mitigating is estimated over the lifetime of the plant (approx 20 years), the price of 74 € was deemed most fitting as to account for this increase. Testing three different prices provides a price range deemed suitable and sufficient to cover an acceptable spectrum of possible estimations.

The last consideration excluding socioeconomic calculations from business economic ones is importation effects. Since Denmark in itself is a producer and exporter of oil-based fuels, the production of electrofuels might as well replace Denmark's production of fossil fuels as it would decrease the importation of this.

External Factors

The external factors affecting the scenarios are the electricity price and the CO_2 emission of the electricity. The electricity price is a variable element influencing the feasibility and cost of producing electrofuels.

As a reference price, the 2019 electricity price and corresponding CO_2 content are used. This price could, however, both be seen to decrease and increase in the operation years of the plant. Because of this, the original 2019 price profile is varied with +/- 20 %, and the effects on the methanol production price is observed from this. One overall assumption is that the CO_2 content of the electricity only decreases as the years go by, and this is therefore not be varied in the same manner as the electricity price.

Plant Product Values

Other than producing methanol, the methanol plant could potentially create revenue from byproducts of the methanol creation process, such as the excess heat production and an exhaust primarily consisting of pure oxygen. The heat could potentially be supplied to the nearby residential areas as excess heat to a district heating grid and the oxygen could be pressurised and sold to other industries.

The quality of the heat produced is assumed to be good enough to provide district heating services. According to (Danish Energy Agency 2017), the operating temperature of the alkaline electrolyzer is 80 °C. Assuming a temperature difference of 10 °Cin the heat exchanger (Lardon et al. 2018), the heat sink could leave the heat exchanger at 70 °C. In addition, this could also be boosted when harvesting the heat produced in the methanol reactor, which operates at 300 °C. It would allow the temperature of the heat provided to be over 70 °Cand be enough for district heating purposes.

Part of the excess heat can be sold to the biogas plant, which can use the heat to speed up the digestion of the feedstock, increasing the hourly production of biogas. This is for instance seen in the BioCat Roslev Project, where a biogas plant consumes around 1 MW heat baseload. The scale of the BioCat Roslev project matches the one used in the present power-to-methanol plant in this report, with a 10 MW electrolyzer capacity. Moreover, the biogas plant CO_2 supply matches the electrolyzer capacity, meaning that a 1 MW heat baseload consumption can be generalised for a 10 MW electrolyzer capacity. (Peschko 2020)

Both of these byproducts could add extra revenue to the plant, and with that increase the profitability of producing methanol through PtX. Different factors does however influence the profitability of selling the heat and oxygen, among these are:

For heat:	**For oxygen:**
Potential heat market	Potential oxygen market
Proximity to the district heating grid	Proximity to CO_2 source
Construction cost of heat offtake	Construction cost of oxygen pipeline
Quality of the produced heat	

Since these factors vary strongly dependent on the placement of the PtX plant, and since this report investigates the socioeconomic effects of PtX at a general level in Denmark, the potential value of oxygen and heat sales outlined above are varied and tested in the sensitivity analysis. An example of the differences in the potential of heat sales to the district heating system can be seen in Appendix B.

The values of the excess heat sold from the plant are corresponding to the price of producing heat from a heat pump. This cost is the stand-alone cost for a 10 MW heat pump working as baseload (Niras et al. 2018). This is deemed adequate to estimate the value of heating, but the results from this should still be viewed as not accounting for the various other influences affecting the profitability of selling heat. This value is then be added as revenue from producing methanol, and the effects are observed. In reality, heat pumps in the Danish district heating systems are relatively new but using heat pumps ensures a conservative approach not overestimating the heat price. On the other hand, the value is potentially underestimated for most district heating systems but the conservative approach is deemed more adequate.

All the elements investigated through the sensitivity analysis are listed in table 4.6 with their corresponding values as outlined and examined in this section.

Sensitivity parameter	**Value used in suitable scenario**	**Ranged Value**
Environmental effects	Cost of mitigating action(74€/ton)	25 €/ton and 200 €/ton
Electricity price	2019 price	2019 price +/- 20 %
Heat sales	No value	Cost of producing heat by other means
Oxygen sales	No Value	Cost of producing oxygen through air distillation

Table 4.6: Summary of the sensitivity analysis parameters.

The values presented in table 4.6 are all tested in the sensitivity analysis in chapter 6, but not all of these contribute to the yearly revenue and with that the NPV. Import effect and employment effects are be presented separately as these are not directly comparable with the traditional economic analysis but should still be considered to better understand the socioeconomics of the investigation. These are therefore presented separately.

4.3.4 Verification of the Energy System Model

The main purpose of the energy system model is to design a power-to-methanol plant and simulate various scenarios which investigates the socioeconomic effect in the Danish context. The model has to be understood based on the theoretical background and specific context within the model is developed which is outlined in chapter 3. According to Sargent (Sargent 2013) the verification and validation related to the model development process, can be done at various stages in this process and on different aspects. Comparing the technical and financial outputs from the model in a subjective approach on an observable system with similar projects can add validity to the model behaviour. However, the novelty status of the power-to-methanol technology in the Danish context disables such comparisons since results and investigations on this specific PtX product from electrolysis in the Danish context are not published.

The verification and validation of the excel model therefore rely on the data validity to be accurate. The data used for the model originates from various source depending on what part of the model it referees to. The technical and financial data for the plant are all from the *Teknologikatalog*(Danish Energy Agency 2020*d*) by DEA and consists of various versions with specific themes. The data for the methanol plant, including the electrolyzer, is found in the version for *renewable fuels* (Danish Energy Agency 2017) while the hydrogen storage is from the version on *Energy Storage* (Danish Energy Agency 2018*b*). From the literature review, it was observed that some of the technical and financial inputs had minor differences compared to the ones observed in the *Teknologikatalog*. Despite these variations, the ones from the *Teknologikatalog* was used as these are presented in a danish context and used by the Danish central administration. In addition, a few inputs from the spreadsheet *Alternative Drivmidler* by DEA was used to provide input on cars and their lifetime expressed in driven kilometres.

The electricity price is obtained through an hourly breakdown of the spot-price for 2019 obtained through Nord Pool's market data (Nord Pool 2018). The hourly CO_2 content of the electricity corresponds to the same hours as the spot-prices and is obtained from the energy data service by Energinet (Energinet 2020*a*). The wind capacity used in the *onsite* scenarios as behind the meter solutions are obtained from Climate Forecast System Reanalysis (CFSR) through EnergyPRO (EMD International 2014). The wind data is applied using calculation methods which are further explained in appendix D. The price of oxygen is calculated from inputs from bio-methanation integrated at a wastewater treatment plant (Lardon et al. 2018). The calculated price is observed to be in the range of the prices found in the literature (Vandewalle et al. 2015) and on this behalf deemed adequate. The excess heat output is found in the *teknologikatalog* but the price used for heat is obtained through literature (Niras et al. 2018) which outline the bench-marking costs for the Danish heating sector and aim to ensure the most cost-effective price for the district heating in Denmark. The heat prices obtained in this report is therefore deemed adequate in the context of this report. Additionally, the price for retrofitting vehicles and the price range for methanol from various production methods was obtained through interviews with stakeholders in the industry of PtX (Jensen 2020).

The data used to create the model is on this behalf deemed valid to be used for the simulation purposes which aim to envisage how the PtX plant can be deployed in the Danish context. The scenarios investigated outline how various key parameters can change both technical and financial depending on how these are included and what the fundamental assumptions are in the model. This relates to the *conceptual model* design outlined by Sargent (Sargent 2013) which are not validated. This validation is not conducted since the model creates a simulation rather than an optimisation. According to Lund et. al (Lund et al. 2017) this adds major uncertainties to the model but since the simulation approach brings attention to political themes through analysis rather than identifying an optimal pathway for power-to-methanol, the importance of these uncertainties and changes are deemed as less important. The model still outlines adequate pathways supported by an explanation of why certain pathways could be more preferable than others. Additionally, Lund et al (Lund et al. 2017) emphasise that the purpose of simulation models is to service and qualify political deliberations and acknowledge that in the end decisions are basically political.

Based on this the importance of the stakeholder analysis increases and the output from the model should be addressed in this context. Overall the model is therefore deemed valid based on the valid data inputs and the operation validity of the model is done iterative through dynamic testing as presented by Sargent (Sargent 2013). Here the input-output relations are addressed and the data correctness of this relationship is observed throughout the development of the model. This is done as incremental steps where additional development to the model and the input-output relations correctness is seen while developing the model. This makes it easier to comprehend the correctness of the relations since only a few relations had to be investigated in each step.

The model is on this behalf deemed adequate based on the data validity, the development process and purpose of the model but also recognise that the uncertainties and complexity linked to reality and changes in the future such as prices and technological development can change the outputs of the model.

4.4 Summary

The research design was developed to answer the research question and used multiple theories and analysis to do so. A summary of how the theories and the analysis are combined to create a pathway for PtX in Denmark before 2030 is shown in Figure 4.6. The technology theory is used to define that the change from fossil fuels to methanol from electrolysis create a radical technology change in the system. In order to implement a radical technology change, the innovative democracy theory can be used to understand how change in society can happen and be facilitated. The Energy System Analysis can provide knowledge of what and how the existing markets need to be changed in order for the new technology to be feasible in the applied context. From this, the organisational levels in which the change needs to happen are identified. The stakeholder analysis then provides knowledge of which groups have the power and importance to promote the change. Moreover, the choice awareness theory suggests four strategies when implementing the changes that create a pathway for implementing PtX.

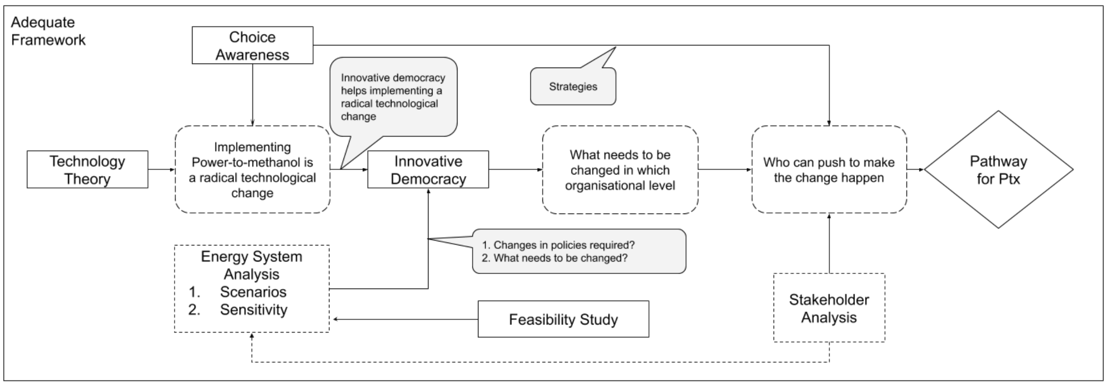


Figure 4.6: Own illustration of how the theories and analysis are connected and affect each other. The figure should not be interpreted in as a linear system, but rather how the analysis and theories were used in the end to come up with a PtX pathway.

Stakeholder Analysis 5

This chapter presents the stakeholder analysis which investigates how the different stakeholders impact the development of PtX in the Danish context. The stakeholders are analysed in order to clarify which entities need to be considered when implementing PtX in a Danish context. Knowing this will enable a clarification of the partway of implementing PtX.

5.1 PtX in Denmark

The stakeholder analysis is performed within the theoretical framework presented in chapter 3 which provides an adequate scope for the analysis. The aim is to clarify how *power* and *importance* are conferred in the stakeholders in regards to developing PtX in Denmark. This investigation focuses on the stakeholders who are part of the regulatory framework and value-chain for PtX and not as such the influence from stakeholders who impose a threat for the PtX development such as the petrol industry. This is shown in Figure 5.1 where the relevant stakeholders are placed accordingly to their power and importance. The supranational EU is also presented since this institution also influences technological development in the Danish context. Their impact is transposed into Danish law and regulations which is why they also indirectly are present in the Danish central administration which is represented by the ministries and national boards. The stakeholder analysis is aimed to include the entire PtX development in the Danish context since the various pathways for this technology are interlinked. Changes regarding RES, CO_2 sources and technological developments in one type of PtX application can as a result potentially affect all PtX pathways in Denmark.

The stakeholders can be aggregated into groups to further understand how their role in the development in PtX can be defined. These groups consist of: *Regulators, producers, suppliers, geographical partners, NGO's* and *Academia.*

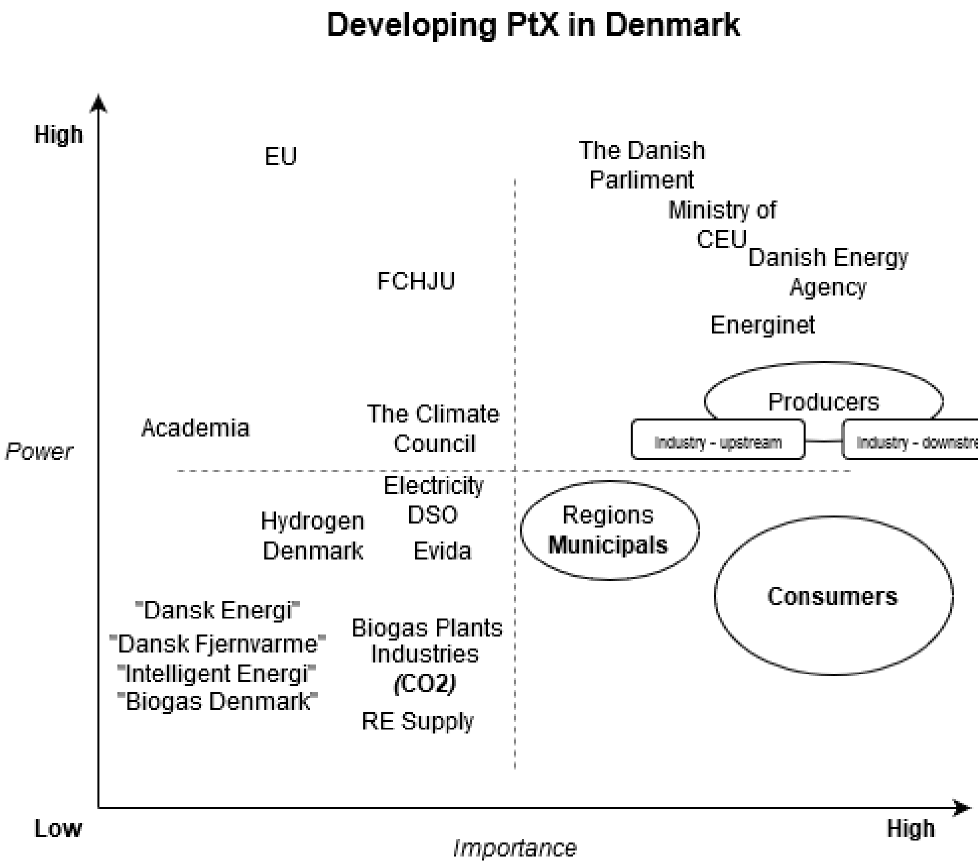


Figure 5.1: Placement of the stakeholders that are influenced or have power in the development of PtX in Denmark.

5.2 Regulators

The regulators group are responsible for developing and changing the laws and regulations that directly or indirectly affect the development of PtX in Denmark. This can be done at various levels and can affect different domains of PtX projects. This group, in general, has both high importance and power.

EU

The EU affects the Danish development by forming the laws and legislation's at the supranational level which determines the overall framework for development, standards and financial supporting schemes that affect the future development in the energy sector. One of the goals of the EU is to reach the common climate goals by providing every European with the access of *secure, sustainable, competitive and affordable energy* (European Commission 2015, Page 2). In regards to PtX, the EU directly affects the development through various laws and legislation's, but also through funding towards projects by the EU sub-organisation The Fuel Cells and Hydrogen Joint Undertaking (FCH-JU) (Fuel Cells and Hydrogen Joint Undertaking 2020). The EU is not considered as one of the most critical stakeholders, due to the distance between the project level in Denmark and the decision-making arena in the EU. So far there has not been any regulation targeted at PtX by the EU, only the renewable energy directive which does not bind the member states to have PtX. However, through their supranational power, they are still capable of impacting the development of PtX in Denmark.

The Danish Parliament

The Danish Parliament defines the regulatory framework and can determine how the PtX sector is developed in Denmark. Through laws, legislation, taxes and subsides the parliament is steering the nation towards the national energy strategies and therefore is seen as the most powerful stakeholder. The energy agreements from 2018 (Regeringen 2018) and the climate law from 2019 (Regeringen 2019) are examples of the power and influence the Danish Parliament has on the development in Denmark. Within the parliament *The Climate, Energy and Utilities Committee* is furthermore assigned to provide inputs to the parliament, propose legislation and bring experts and politicians together by hosting hearings in regards to the committees' subject area. This committee also discusses PtX and envisages a potential future joint strategy for PtX where for example road transport, shipping and aviation are potentially required to use electrofuels made at demonstration plants before 2030 (Auken 2020).

Ministry of Climate- Energy and Utility *(CEU)*

The ministry facilitates the decisions made in the parliament and strategically strives to ensure a secure and efficient energy sector both now and in the future through sustainable development (Ministry of Climate-, Energy and Utilities 2020). Their role is therefore to link the short-term perspectives from the changing governments to the strategic long term perspectives as listed in Figure 1.2 on page 4. The ministry has high power and importance in regards to PtX development in Denmark.

Danish Energy Agency *(DEA)*

The Danish Energy Agency provides analyses, outlooks and reports to create an adequate information basis for the parliament and then execute the decisions made by parliament. The DEA acts as the executive sub-organisation of the ministry of CEU and the Danish parliament and aims to secure the energy supply in the future Danish society. (Danish Energy Agency 2020*c*) The reports from the DEA are prepared using information about technology, environment and economy from the *"Teknologikatalog"* which is developed in cooperation with Energinet (Danish Energy Agency 2020*d*). They are both important and powerful since they analyse and evaluate which direction of development would be beneficial for Denmark and facilitates support through the "Energiteknologiske Udviklings- og Demonstrationsprogram" (EUDP) which can help facilitate various energy project in the technological development phase.

The purpose of the organisation is therefore to ensure sustainable energy development for Denmark in the future, considering a good balance between established and new technologies. However, their focus is more on developing the energy system to have a high security of supply and competitiveness. The purpose of the organisation is therefore to ensure enough sustainable energy for Denmark in the future while investigations into future technologies with an uncertain potential also is relevant, but the core purpose to investigate. Providing support to demonstration projects and otherwise monitoring the PtX development closely while investigations on PtX in the Danish context is a relative new area within the DEA. (Egestrand 2020) The current position of the DEA is to provide support to demonstration projects and otherwise observe how the PtX sector develops until 2030.

Energinet (electricity and gas TSO)

Energinet is a public independent company beneath the ministry of CEU. They are the Danish electricity and gas TSO who owns, operate and develop the danish transmission grid to ensure supply now and in the future. (Energinet 2020*c*) The financing of Energinet is through TSO tariffs which are structured so they only cover the necessary costs[1](Energinet 2020*f*). This regulation is decided through the laws and legislation's from the central administration and monitored by the danish supply monitoring agency *"Forsyningstilsynet"*. Energinet furthermore helps in the development of the *"Teknologikatalog"* and analyse from where and how the future electricity and gas demand can be met. As part of this, they are also engaged in various consortia which received funding from the EUDP (GreenLAB, Shell) and as such involve themselves actively in the PtX development. Energinet have furthermore outlined the large potential for PtX in Denmark in various analytical reports such as *System Perspective 2035* (Energinet 2018), *System perspective for the 70%-target and largescale offshore wind* (Energinet 2020*d*) and *PtX before 2030 in Denmark* (Energinet 2019). The core business is still the development and maintenance of the electricity grid, but since PtX consumes large amounts of electricity (preferably from fluctuating RES) and some products can be injected into the gas grid, Energinet will be affected by the PtX development in Denmark.

Evida

Evida is a public independent company owned by Energinet who operates, maintains and install the gas distribution network in Denmark (Evida 2020*a*). The company is regulated through laws and legislation which regulate income come regulations which are by the DEA and the danish supply monitoring agency *"Forsyningstilsynet"* (Evida 2020*b*). Evida handles a critical part of the infrastructure which is needed for power-to-gas projects with grid injection. Moreover, having more green methane in the grid helps to increase the percentage of renewable gas in the gas grid. Overall they are regarded to have some importance and some power.

[1]In danish; *hvile-i-sig-selv princip*

Electricity DSO's

There are various electricity DSO's in Denmark, which are responsible for the deliverance of power from the transmission grid handled by Energinet to the end-users. The electricity DSO are regulated through income regulations, benchmarking and efficiency requirements by law and legislative measures decided by the central administration and monitored through the aforementioned *Forsyningstilsynet*. Tariffs are charged to develop and maintain the distribution grid and vary depending on the DSO area. These are perceived as relevant stakeholders since they are providing essential infrastructure at the local level and defining the DSO tariff at the site in which a potential PtX projects are situated.

5.3 Producers

The producers can be defined as the *"PtX industry"* which are the companies that are directly involved in the PtX sector by designing, structuring and administrating the PtX projects. The producers can be distinguished as either being *upstream* which concerns development and sales of the PtX equipment and technology and *downstream* who are the ones developing and selling the technology that consumes the electrofuels. The producers, therefore, have large importance and interest in PtX to become developed to the point where it can be competitive and market-ready. A non-exhaustive list of some of the larger stakeholders involved in the Danish projects which are presented in Figure 1.8 on 13 are: *Everfuel, Dansk Shell, Hydrogen Valley, Greenlab Skive, Re::integrate, Electrochaea, ect.*

5.4 Suppliers

The suppliers consist of the "producers/owners" of the RES and CO_2 sources which provide the electricity and CO_2 essential for both hydrogen production and the processing into electrofuels.

RE supply

The sustainability of PtX is crucial for this project. Therefore the electricity sources used for PtX needs to be renewable and suppliers of this electricity are therefore also included as stakeholders for PtX. The RES suppliers are indirectly benefited from PtX development, being able to sell electricity at higher prices if the electricity consumption increases and having more potential customers. However, these stakeholders do not have any stake in the development of PtX, and their interest is foremost viewed as being the financial opportunities to sell their energy production.

Biogas plants (CO_2 supplier)

Biogas plants have the opportunity to supply CO_2 from their processes which can be used to produce some types of PtX. The biogas plants potentially can benefit if the CO_2 market develops and it starts to become a valuable resource. In addition, the biogas plant can potentially benefit from excess heat generated at the PtX plant which can be used to increase the efficiency at the plant. The biogas plants can furthermore be potential owners of a PtX plant as part of the biogas plant and would then move to be part of *producer* group.

Industry (CO_2 supplier)

The industry can potentially provide CO_2 which can be used to produce some PtX products. Getting the CO_2 as a point source from the industry requires Carbon Capture technology but can help the industry toward a more sustainable utilisation of their emissions in other products. The industry can also be owners of the PtX plant and utilise the captured CO_2 in a PtX product which can be used in the industrial processes and thus reducing their emissions even further. This can be applicable in some industries and in such a case the *industry* would move to become part of the *producer* group.

5.5 Geographical Partners

The partners take part in the development and are often seen as part of the consortium's developing PtX in Denmark. The partners include various regions, municipalities and potentially other location-based groups who can be interested in attracting the PtX facilities locally. This can be done based on the interest of reaching climate goals, generate industrial symbiosis or secure job creation and in general ensure local development.

5.6 Consumers

The consumers' group are important but do not have a lot of power as such in the development of PtX in Denmark. However, the consumer group set the demand for PtX products and therefore have power through demand which affects the supply. The consumers are the end-users of the PtX products which, depending on the product, can be utilised in different sectors and therefore aimed at different consumer groups. The consumers can be private people using the products for transportation, but can also be used in the commercial sector for heavy-duty transportation, shipping and aviation. The industry can furthermore use some products for industrial processes while the electricity and heating sector can us PtX products as a sustainable way of providing fuels where otherwise non-sustainable fuels are necessary to meet the demand. The different consumer groups can be derived from Figure 1.6 on page 11 where the PtX products utilisation is presented. It is furthermore important to mention, that through byproducts from the PtX plant a new supply of excess heat and O_2 can be used to meet a demand, which is in addition to the actual consumption of PtX products.

5.7 NGOs

The Non-governmental organisations are advocating and facilitating the interest of their members. The NGOs represent different interest groups and take part in the public debate about PtX and provide information to decision-makers in the member areas of expertise. NGOs such as *Hydrogen Denmark* can also be directly by pushing for the development of the PtX on a general scale. The NGOs can also be indirectly involved like *Dansk Energi, Dansk Fjernvarme, Integlligent Energi* and *Biogas Denmark* where the organisations' interests are related or affected indirectly by the development of PtX.

The Climate Council is an independent expert body created by the Danish parliament to advise the Danish Parliament towards the most cost-effective pathway towards a net zero-emission society in 2050 (The Climate Council 2020). They are as such an NGO but have emerged through the government, which is why their independence to some extend can be questioned. In their report on how to reach the 70% emission reduction target they envisage PtX as a supplement to direct electrification, but PtX nevertheless is seen necessary in the long term (Klimarådet 2020*b*, P.121). Furthermore, a large emphasis in the report is on Carbon Capture Storage (CCS) while the Carbon Capture Utilisation (CCU) is seen as a non-feasible alternative since fossil fuels costs and heat cost are estimated to decrease in price and thereby worsen the condition for CCU and then indirectly some PtX products. (Klimarådet 2020*b*)

5.8 Academia

The academia provides research and knowledge on the technical, economic and societal aspects of PtX. These institutions take part in the public debate and provide input to the parliament in regards to the future development of PtX in Denmark. The academia furthermore challenges the energy scenarios for the future made by DEA with alternative scenarios for the future development of the Danish energy system as seen in the IDA scenarios (Mathiesen et al. 2015). The academia researches all components of technology, as presented in Figure 3.5 on page 24 in regards to PtX to make an objective analysis of PtX development in Denmark. As such, they can create new knowledge and promote technology through this knowledge and affect the public and governmental opinion of PtX but other options are also investigated.

5.9 Stakeholders in Innovative Democracy

The analysis of the stakeholders shows the different stakeholders' power and importance in regards to the development of PtX in a Danish context as presented in Figure 5.1. Since the *most critical group* of stakeholders is predominantly represented by the central administration in Denmark, it becomes clear how these can affect and potentially dictate the development of PtX to a large extend. The Danish context is nonetheless democratic, which is why these stakeholders can be impacted by the changing political agenda in the democratic process. An agenda which within the last year has put emphasis on the importance of PtX in the public debate (Egestrand 2020). This increasing publicity and debate on PtX can either create a positive or negative direction for the development and future considerations of the technology and its placement in society. This aspect is highly affected by the approach towards the current institutional composition and market economy. As presented in chapter 4.1 on page 30 this report investigates the research question through the innovative democracy model. The stakeholders can be observed through this approach which provides a deeper understanding of how they potentially can affect the future of PtX. The placement of the stakeholders within the innovative democracy system approach can be seen in Figure 5.2.

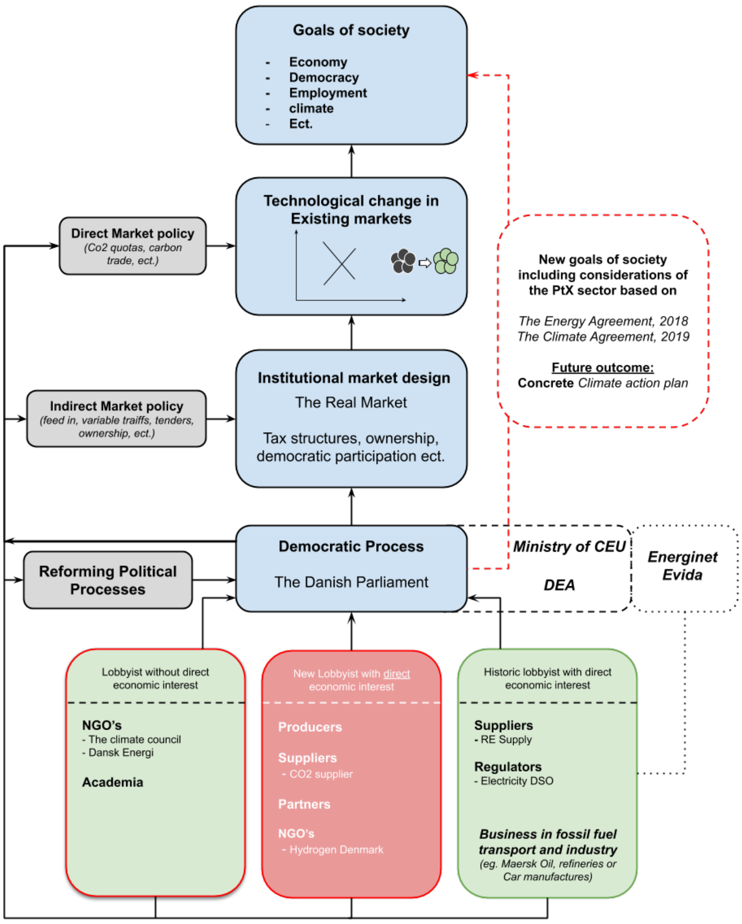


Figure 5.2: Innovative democracy illustration with placement of select stakeholders.

Figure 5.2 outlines the basic structure of innovative democracy and how the stakeholders from the analysis are part of the institutional and market structures. *The Ministry of Climate, Energy and Utility* (ministry of EUC in Figure 5.2) and *DEA* is part of the central administration and therefore can be said to be situated within or at the border of the democratic process. In the same manner are *Energinet* and *Evida* independent companies but publicly owned. As such, their role as a *historic lobbyists with economic interest* can be considered from their historic relation to the central administration and subsequently also the Danish Parliament. This understanding of the stakeholders is illustrated by having them linked by permeable boxes linked to the Democratic Process in Figure 5.2.

The outlined stakeholders in the different lobbyist groups are observed to have a direct effect on the Democratic Process and the Reforming of Political Processes. This reformation of political processes can result in new goals of society (red dotted line) which subsequently can restructure the entire system (blue boxes). From the understanding in the theoretical framework in Chapter 3 on page 18, such a change is understood as part of the *first order governance system* why this only can be changed throughout political processes on a long term basis. This change, therefore, requires fundamental changes in society and the structure of the system. Change in the system on a short term basis is observed as a result of the lobbyist groups effect on indirect and direct market policy. These changes in direct and indirect market policy are mainly seen as a result of the democratic process. Changes towards the same direction for a long term or fundamental changes in society can set a new regime that changes the goals for society. The dotted red line is seen as a consequence of a reformed political process through the innovative democracy but is considered a long term change.

The stakeholder analysis shows how the power in the central administration can be a possible barrier or enabler if PtX technology is to be part of the existing markets. An open and inclusive democratic process which is emphasised in Figure 5.2 shows how the *new lobbyists with economic interest* involved in the PtX sector are important in the political process and if necessary empower these since they potentially do not have any power compared to the *historic lobbyists with economic interests*. Reforming the political process can, therefore, be necessary to increase the inputs from *lobbyists with no economical interests* or *new lobbyists with economic interest* in the democratic process before a radical technological change towards PtX can emerge in the existing markets. This can however also emerge from some *historic lobbyist with economic interest*. As outlined in Figure 5.2 the ties between otherwise independent stakeholders and the central administration can potentially create a situation where development is seen as the concrete institutional approach, where decisions are decided by historically strong and influential institutions. *Historic lobbyists with economic interest* can therefore also promote the development towards a successful PtX implementation. This depends on the specific lobbyists' interest in PtX why they can either create or obstruct a potential pathway for the PtX development before 2030. However, the risk linked to this lobbyist group is that they potentially want to influence the development in order to best facilitate their existing investments in a changing environment. An example of this is the new proposed plans for a large scale PtX plant where *historic lobbyists with economic interest* (Maersk, DSV Panalpina, DFDS og SAS) who currently rely on fossil fuel products are the main driver behind the plans (Ingeniøren 2020).

An active policy of participating in the development is taken by these lobbyists but they also have existing investments relying on fossil fuels which can impact the development. As displayed in the figure, the historic lobbyists include various stakeholders hidden in the *Business in fossil fuel transport and industry* who are not investigated in this report since they do not have stake in the future of PtX but merely can be affected negatively. This stakeholder group nonetheless have importance since they have been part of the existing infrastructure system in Denmark for decades and have been providing the resources for mobility in the Danish society. For these businesses, a shift towards PtX can result in a decreased income, which is why these could have a potential interest in affecting the political process to move against PtX in the future.

Based on the Danish political agendas and agreements presented in table 1.2 on page 4 it should be obvious that their business will decrease significantly in the next 30 years, regardless of the PtX development. Delaying and keeping the existing paradigm can therefore be beneficial for these stakeholders unless they change their current business model. This is for instance the case of *Dansk Shell*, which core business is to supply fossil fuels to mobility, who also push for PtX which can be used at their refinery in Denmark. This involvement can be observed later in Figure 5.3. Enablers of PtX are also seen in the historic lobbyist where RE suppliers and electricity DSO which can foresee potential incomes with PtX depending on how PtX is structured in Denmark. If PtX is deployed in Denmark an additional demand for electricity will occur which will require more grid infrastructure to handle the new RES which is necessary for the danish consumption. As such, the core business of the electricity DSO and the RE suppliers would potentially increase with an added electricity demand. The three various lobbyists can therefore not be aggregated as being for or against a future of PtX since this will vary depending on the actual interest or entanglement into the PtX development. This is largely due to the fact that major changes towards a more sustainable system are inevitable to happen, while it is just the speed and direction of this that can change. The entanglement of stakeholders can be seen in Figure 5.3 where the two last PtX projects in Denmark to receive funding are displayed together with the involved stakeholders. Figure 5.3 furthermore shows the central administration (blue boxes) and how these are linked within. *Energinet* is also presented here and can be observed to be part of both projects.

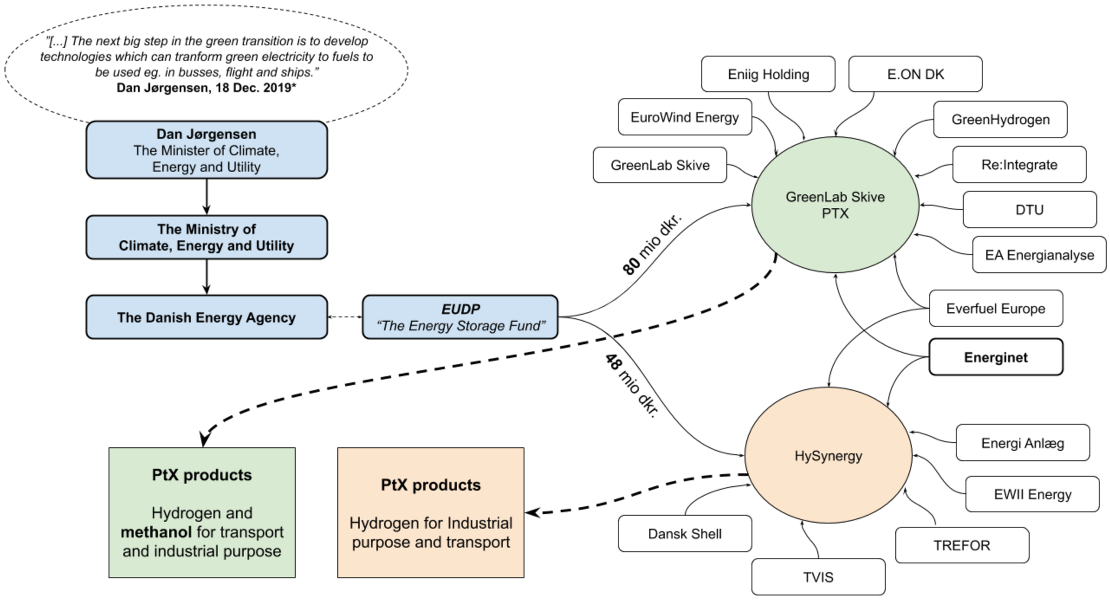


Figure 5.3: The role of the central administration and the many stakeholders seen involved in PtX projects (The Danish Energy Agency 2019). (Quote in figure (The Ministry of Climate, Energy and Utility 2019))

From the interviews and literature analysis, it is seen that apart from the *new lobbyist with economic interest* and *Energinet* push for more development in the Danish PtX scene while the political framework and the *DEA* are more hesitantly. Energinet can as such also be seen as part of the *"PtX industry"* which naturally is pushing for the PtX sector to develop as they have economic interests. The more hesitantly position of the DEA is taken since their main purpose is the ensure energy and not as such investigate various potentials which can be plentiful. The political framework is to some extend pushing for the development but are also affected by the fact that 70% of CO_2 emission is to be reduced and PtX is not an inexpensive solution towards this goal. The political side can as such be limited to choices which can be described as *No regret* choices which represent a low-risk but attractive strategy for the politician's (Philanderer & Golson 2012). Here electrification is for example favoured since the efficiency and the simplicity is considered to make it the better solution. However, electrification can also become problematic and cause unbalance in the electricity grid, why other solutions such as the more centralised PtX production are easier to control.

The stakeholder analysis outlines how the development of PtX is affected by the various stakeholders in relation to power and importance. This analysis, therefore, outlines how the stakeholders and especially the political agenda impacts the development of PtX in Denmark. The high power in the central administration can be important for PtX which currently is not economically sustainable due to PtX being a novelty sector where its products are competing against cheap fossil-based counterparts such as petrol, diesel and natural gas. But power and importance can also be increased or decreased in certain stakeholders throughout laws and legislations. The TSO and DSO's are limited by regulations on their economic activities which can potentially change in the future. Depending on how the change affects the stakeholder, their position in Figure 5.1 can change. Changes in the regulations of the TSO and DSO's in Denmark is mentioned as a possible future in the governments' strategy *Forsyning for fremtiden* (Regeringen 2016). In this strategy, an agreement based approach is mentioned which can enable the TSO and DSO's to make agreements about their future economy. This can allow the TSO and DSO's to have more flexible regulation to encompass actual needs and changing conditions to accommodate socioeconomic measures. The power of the TSO and DSO's would therefore increase in Figure 5.1 if their roles are changed. Additionally, the stakeholder *Forsyningstilsyn* would also need to be included, since they have importance and power in relation to the agreements which they can approve or refuse.

Regardless of these possible effects on change in stakeholders, the conducted analysis outline that development of PtX can be changed the various impacts (grey boxes) presented in Figure 5.2. Here indirect market policy can change the institutional market design and the technological change in the existing markets can be effected through direct market policy. Knowing how and where changes can be implemented therefore provide an insight into how short term changes in the political framework through policy and inclusion of new lobbyists can help to develop the PtX sector.

This knowledge is valuable in the energy system analysis where and actual PtX plant in the Danish context will be modelled. The business economy related to a PtX plant is not expected to be feasible and therefore it is less likely to be developed. However, if the socioeconomic parameters related to the plant are included the feasibility study of the plant can potentially change to be feasible. The elements from *Choice Awareness* theory presented in section 3.4 on page 25 are therefore important to consider for a near-future PtX plant. In the theory, it is furthermore important to understand that political decisions do not occur in a political vacuum. This influence is outlined throughout this stakeholder analysis and observed through the innovative democracy approach. Through this approach, the various possible points which can create a change in the system are furthermore presented (grey boxes). The impact by the stakeholders and especially the ones in the central administration in Denmark can therefore be observed to impact the PtX plant feasibility through direct or indirect policies as outlined in Figure 5.2. In the same manner, a potential lack of policies which can be related to a more neoclassical approach can create a difficult situation for radical technological change in the existing market. This mainly related to the organisational element of technology and is concertised through policies that affect input values and calculation methods which affect the results of PtX in the Danish context.

Investigating the plant design through a feasibility study based on the important elements from the choice awareness theory presented in section 3.4 on page 3.4 can, therefore, create a new situation where PtX becomes feasible if additional parameters such as climate mitigation are considered in the feasibility study. This can provide additional input to the discussion of the role of PtX before 2030 in the Danish context.

Energy System Analysis 6

This chapter presents the energy system analysis conducted throughout this project which is aimed at clarifying the societal potential of PtX in Denmark. To do this, the analyses investigate what is estimated to be the most societal profitable solution for creating methanol from electricity and test the sensitivity of these plants. The chapter initially describes the plant design of the PtX plant, then describe how the model is constructed, what data is used and what controls the operation of the plant, describe the output of the plant, and lastly present the results of the plant in an economic analysis of the lifetime operation. The results also include a sensitivity analysis and a discussion of the upscaling of the plant.

6.1 Plant Design

This section presents the choices made for designing the plants used to produce electrofuel. Figure 6.1 shows an overall representation of the choices made in regards to produced fuel, technology use and material sources. This pathway is chosen since it can be utilised in the existing market without major changes to the stationary infrastructure and the willingness to pay for such products are estimated to increase in the future (Energinet 2019). The production of methanol is furthermore the most simple product to create seen from the production side which can be incorporated into petrol as a drop-in on behalf of bioethanol (Zeuthen 2020). If the methanol product is to be used directly and as the main component in the fuel for vehicles, an added investment of retrofitting the vehicles also have to be included. Power-to-methanol production is a good starting point for PtX applications because it can also be utilised to produce more complex electrofuels such as DME.

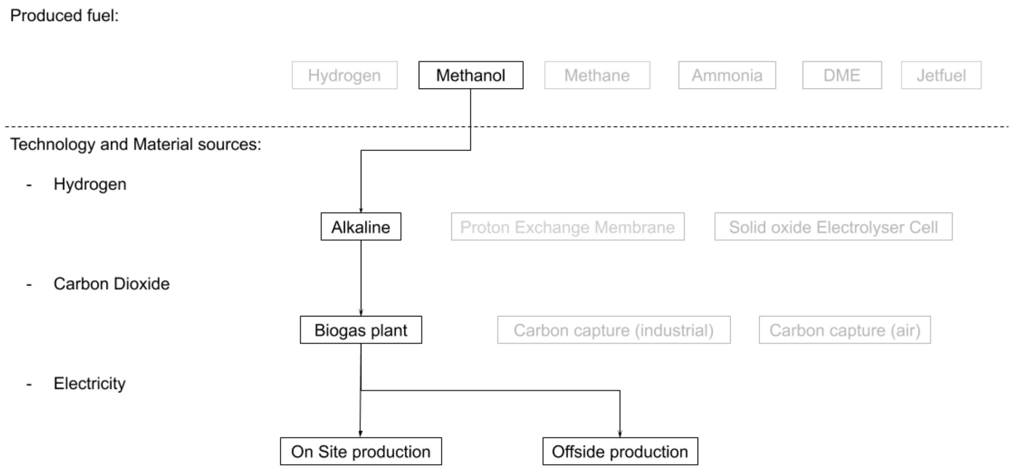


Figure 6.1: Elements and considered options of pathways for PtX.

As seen in Figure 6.1 and presented in section 1.4 on page 10, methanol was the chosen fuel. Methanol is a hydrocarbon that is in liquid form in normal temperature and pressure (NTP) with the formula CH_3OH. Methanol electrofuel production uses electricity and CO_2 as input and produce heat as a byproduct. The overall efficiency for power-to-methanol is that around 60% of the electricity consumed is transferred to the methanol molecules, while most of the remaining 40% is converted into usable heat (Danish Energy Agency 2017).

6.1.1 Hydrogen supply

The PtX pathway of producing methanol requires hydrogen through electrolysis. The method of conducting electrolysis has a high impact on the efficiency and cost of a PtX project. The various methods of producing hydrogen by electrolysis are as seen in Figure 6.1 through Alkaline, Proton Exchange Membrane (PEM) and Solid Oxide Electrolyser Cell (SOEC). Alkaline is the oldest and most established of these technologies which is seen when comparing the financial data of them, as presented in Table 6.1.

Input	Alkaline	PEM	SOEC
Efficiency	61.2 %	58%	76 %
- Heat input	-	-	15 %
- Electricity input	100%	100%	85 %
Lifetime	25 years	15 years	20 years
Investment cost (M€ pr. MW)	0.60	1.1	2.20
Total Operation cost (€ pr. MW)	30 000	55 000	66 000
Usable heat output	14%	-	3%

Table 6.1: Technical and financial data for the various methods of conducting electrolysis. (Danish Energy Agency 2017)

Table 6.1 shows that while alkaline is not the most efficient technology, it is the cheapest and longest-lasting of the electrolysis technologies. It does also have a high potential of excess heat, which could be used in the industry or supply the district heating and thereby create an added revenue (Danish Energy Agency 2017). The principle behind the alkaline electrolysis is having an anode and a cathode circuit inserted into a water-electrolyte mix. Conducting electricity through this will make the anode and cathode act as two poles pulling the water molecules apart, leaving $H+$ in the cathode end and $OH-$ in the anode end. The $H+$ receives the electrons from the current running through the cathode and turn into H_2. Since H_2 has a lower boiling point than water, the H_2 separates as a gas which can be stored. The current industrial standard for the operating temperature and pressure is 80℃and 30 bar.(Danish Energy Agency 2017) This means that if an alkaline electrolysis were to function as a flexible electricity demand the startup time will include heating of the water until the desired operating temperature has been reached. By having the water constantly heated the startup time could be significantly reduced, but this would also create a constant heat demand which should be included as an energy demand for the system. Generally speaking, alkaline is not as flexible as a PEM electrolyser, but the estimated 15 minutes start-up time for the alkaline (Danish Energy Agency 2017) is deemed acceptable for the purpose of this investigation. There is no mention of any start-up costs in the Technology Catalogue under the alkaline electrolyzer section, but in the power-to-methanol section, the start-up costs are assumed to be 0 (Danish Energy Agency 2017). Therefore, the start-up cost is assumed to be 0.

6.1.2 CO2 supply

Besides hydrogen, CO_2 is also required to produce methanol. The CO_2 can be captured from the exhaust of heavy carbon-emitting industry, directly from the air, or taken from the exhaust of upgraded biogas plants. Carbon capture equipment does, however, have its own energy requirements, and would ultimately decrease the total efficiency of producing electrofuel, while also increasing the costs. To avoid this, the plant is designed to act in combination with a biogas plant, where the gas has been upgraded to fit the natural gas grid. This upgrade ensures that the burning value of the gas is increased by removing CO_2 from the gas(Danish Energy Agency 2017). This byproduct of CO_2 can have a purity up to 99%, and can be used directly into the PtX process.

6.1.3 Electricity Supply

The electricity supply is essential for the PtX plant and is in this report considered and modelled in two different ways: *Offsite*, where the electricity is imported from the grid, and *Onsite* where behind the meter wind turbines in combination with the grid provide electricity to the plant. The *Off site* is a much simpler solution that does not require the plant to be placed at locations with a high wind potential which is the case of the *Onsite*. The two main disadvantages of the *Off site* plant are nevertheless the tariffs on electricity consumed which have to be paid on top of the spot price and the fact that electricity from the grid does not enable as high a level of carbon neutrality as that of electricity produced by onsite wind turbines.

For the *Onsite* solution the electricity is mainly supplied from the wind capacity and potentially topped up with electricity from the grid. This means that if the wind power generation is higher or equal to the plant's consumption, then all the electricity consumed by the plant will come from the local wind capacity. In the case of the local wind source providing less electricity than the consumption at the plant, then the difference is supplied from the electricity grid. The option of supplying power to the plant from the grid in this solution is important, to overcome the lack of flexibility linked to the methanol reactor (Danish Energy Agency 2017).

The electricity from the local wind turbine is considered CO_2 neutral and does not have to pay tariffs since it is considered being behind the meter where the RES is directly used in the plant which is an option in the Danish context (Skatteministeriet 2017, §2, litra c) Even though the current regulation requires the production and consumption facility to be at the same cadastre, this restriction is disregarded in this report. The electricity produced at the local wind capacity is, therefore, more advantageous to us compared to the electricity from the grid. Even though the *onsite* has a clear advantage, it is not as simple to implement as the *offsite solution*, due to it requiring both space and building permissions for the wind turbines required. For this reason, both types are considered throughout the analysis. The onsite solution can potentially create some local conflict in regards to wind turbines and their placement which have to be considered in the planning perspective of the envisaged plant. These concerns are however disregarded in this report and are only briefly discussed in Chapter 7.

Electricity Costs

When buying electricity from the grid, DSO and TSO tariffs are added to the electricity price. These tariffs are used to some extent to maintain the grid and to cover investments into the electricity grid and connections. The TSO and DSO tariffs can be seen in Table 6.2. The TSO values used were for 2020, while the TSO values used were the average tariffs for a *B low connection* in Western Denmark in 2018. It is assumed that a higher voltage connection would require further investment into transformer and infrastructure.

Fixed Cost	**øre / kWh**
TSO tariff	9.89
DSO tariff	10.11
DSO subscription fee	0.54
DSO overarching fee	0.19

Table 6.2: DSO and TSO tariffs used in the analysis. The TSO tariff was obtained from (Energinet 2020*e*), while the DSO tariff was taken from the report made by Dansk Energi (Energi 2020).

When considering the *onsite* solution, the wind turbines investment cost and revenue for excess electricity produced are not included. It is assumed that wind turbines would be willing to sell the electricity at the spot price. It is assumed that less future wind projects will require any form of subsidy, as it in the case of the future wind turbines at Hirtshals Havn (State of Green 2019). For both solutions, the CO_2 content of the electricity consumed is accounted for in order to meet the renewable fuel requirements as mentioned in section 4.3.3 on page 43. Additionally, the expenses of running the *off site* scenario are higher due to more electricity being purchased from the grid, which includes tariffs. To see if this creates a general better value for the PtX plant, both types of electricity supply are investigated since both are considered viable options when it comes to large scale implementation of electrofuels into the danish society.

6.2 Model Construct

This section presents the values and considerations used for modelling the tested plant and designing its operating patterns. The modelled plant will originally only consist of an alkaline electrolysis, a methanol reactor and hydrogen storage to provide flexibility in the production. An illustration of the overall plant is shown in Figure 6.2.

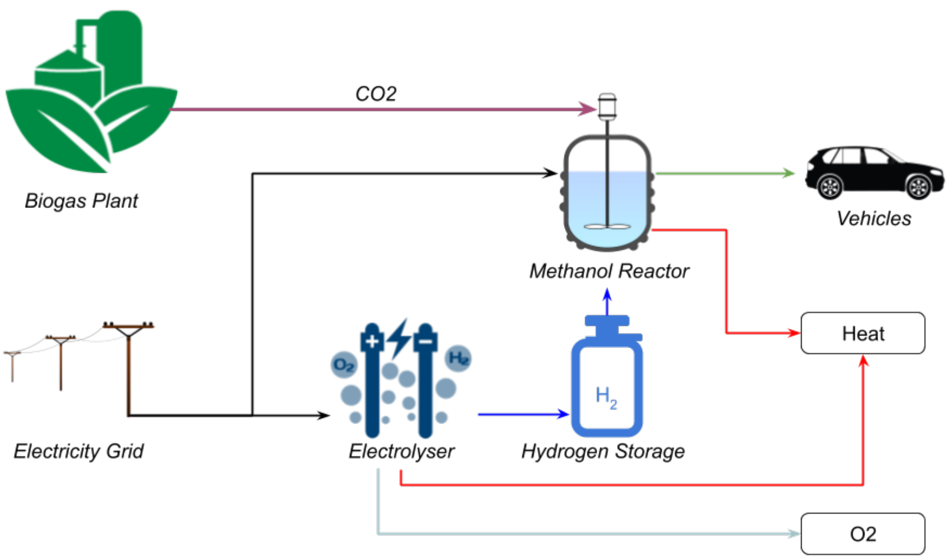


Figure 6.2: Illustration of the overall modelled plant.

Figure 6.2 shows the modelled plant including its inputs and outputs which are key to understand the potential value streams and costs related to the plant. To provide a more thorough insight into what happens at the methanol reactor, which is essential for this report, the reactor processes are shown in Figure 6.3. CO_2 and H_2 enter the reactor, while electricity is used for compression. After the reaction takes place, water and methanol are generated and then separated in a distillation process. The water that comes out can potentially be reused in the electrolyzer.

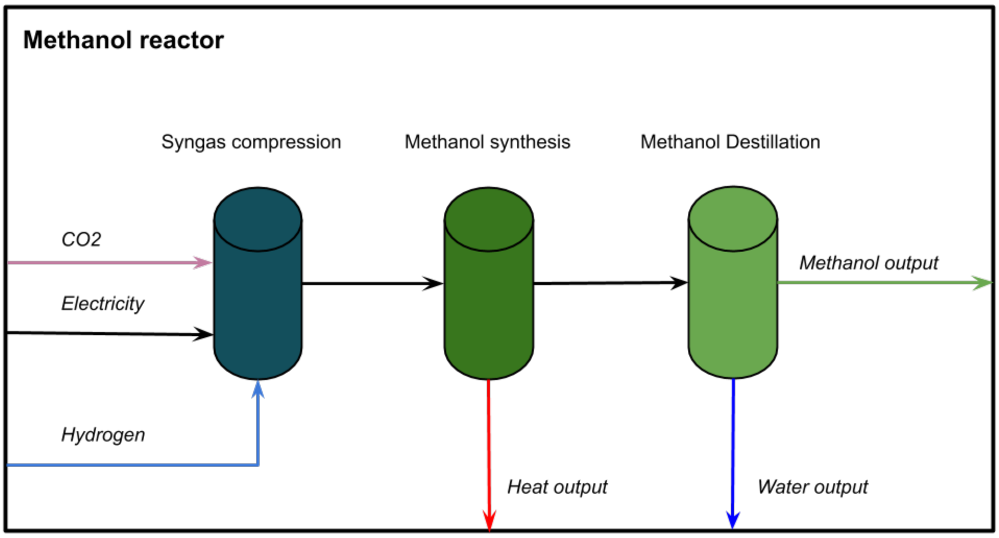


Figure 6.3: Detailed illustration of the methanol reactor as shown in Figure 6.2.(Danish Energy Agency 2017)

6.2.1 Used Data

The values used for modelling the PtX plant are based on those presented in the *Teknologikatalog* by the DEA (Danish Energy Agency 2017). The original values used for the methanol plant are presented in table 6.3.

Variable	**2020 value**
Input	
- CO_2 consumption	1.37 t/t Methanol
- Hydrogen consumption	0.192 t/t Methanol
- Electricity input	1 MWh/MWh total input
Outputs	-
- Methanol output	0.58 MWh/MWh electricity input
- District Heating output	0.25 MWh pr. MWh electricity input
Additional information	-
- Planned outage	2 weeks per year
- Technical lifetime	20 years
Financial data	-
- Specific investment	4.51 M€/MW Methanol
- Fixed O&M cost	53 000 €/MW methanol
- Variable O&M cost	6.27 €/MWh

Table 6.3: Technical and financial data for the methanol plant used for testing the socio-economic feasibility of PtX. (Danish Energy Agency 2017)

In the *Teknologikatalog* (Danish Energy Agency 2017), as presented in Table 6.3, it can be observed that while the typical plant size changes from 3 MW to 33 MW between the 2015 and 2020 data entries while the investment cost pr. MW methanol produced remains the same. Based on this it is assumed that scaling a plant within these limits, results in a linear scaling to the price.

The plant which data is used consists only of a alkaline electrolysis and a methanol reactor. Here the alkaline electrolysis has relative flexibility of 15 minutes shut down and startup from hot standby, whereas the methanol reactor is best kept running for optimal efficiency. While the values presented in table 6.3 are an overall representation of the plant, Table 6.4 shows the specifics of the alkaline electrolysis used in the plant.

Variable	**2020 value**
Inputs	
- Electricity input	1 MW
Outputs	-
- Hydrogen output	0.64 MWh/MWh electricity input
- District Heating output	0.14 MWh pr. MWh electricity input
Additional information	-
- Technical lifetime	25 years
Financial data	-
- Specific investment	0.60 M€/MW Methanol
- Fixed O&M cost	30 000 €/MW methanol
- Variable O&M cost	0 €/MWh

Table 6.4: Technical and financial data for the alkaline electrolysis part of the plant used for testing the socioeconomic feasibility of PtX. (Danish Energy Agency 2017)

In the standard methanol plant, it is seen that the alkaline electrolysis uses approximately 94% of the total electricity demand. As explained in section 4.3.3 on page 43, the criteria of an average CO_2 reduction of 551 gram pr. kWh is used to determine the hours that are eligible for hydrogen production. Given that the methanol reactor has to run at all times except for the forced outage of two weeks annually, the flexibility of production relies on the hydrogen production. To accommodate this flexibility, a hydrogen storage capacity is required and the hydrogen production capacity of the electrolyser has to be higher than the hydrogen consumption capacity of the reactor. Here the storage used is a steel tank storage solution with a capacity of 16.7 MWh pr. unit (Danish Energy Agency 2018*b*). Its application in this project is to act as a short term storage for the hydrogen between the electrolysis process and methanol production, why the steel tank was chosen instead of other candidates of hydrogen storage. The storage and the added capacity of the electrolysis allow for extra hydrogen to be produced, stored, and utilised in hours where the CO_2 content of the electricity is above the allowed limit and hydrogen as a consequence is not produced. Table 6.5 shows the basic data for this hydrogen storage.

Variable	2020 value
- Energy storage capacity pr. unit	16.7 MWh
- Roundtrip efficiency	88 %
- Technical lifetime	25 years
Financial data	-
- Specific investment	0.057 M€/MWh hydrogen
- Compressor component	0.03 M€/MWh hydrogen
- Fixed O&M cost	600 €/MWh hydrogen
- Variable O&M cost	0 €/MWh

Table 6.5: Technical and financial data for steel tank hydrogen storage used for testing the socioeconomic feasibility of PtX. (Danish Energy Agency 2018*b*)

The roundtrip efficiency account for the energy losses from pressurising the hydrogen and general losses of process. This efficiency can be expressed as seen in the following equation:

$$\eta_{roundtrip} = \frac{E_{hydrogenOut}}{E_{hydrogenIn} + E_{compression} + E_{permeatedHydrogen}} * 100\% \tag{6.1}$$

For the steel tank storage, the permeated hydrogen is assumed to be zero, which is why the energy consumption only consists of the electricity required for compressing the hydrogen. For one full steel tank, this corresponds to approximately 2 MWh. The investment into a methanol storage is assumed to be negligible, as it would require similar storage solutions as petrol.

The storage costs, as seen in table 6.5, can quickly become a large part of the investment price since the flexibility is largely tied into how much excess hydrogen production can be stored doing favourable production hours. Therefore, it is deemed important to find a suitable scaling of the methanol reactor, the electrolyzer and the hydrogen storage to minimize the costs while still meeting the predefined criteria that are set. The method of doing this is presented in the following section.

6.2.2 Model Scaling and Operation Pattern

To scale the modelled plant and design the operation pattern, the CO_2 profile of the electricity consumed is considered. This is done to match the production hours to those containing less CO_2 pr. MWh than the maximum allowed limit, as discussed in section 4.3.3 on page 43. Here the CO_2 profile of the electricity for 2019 is used. Considering the efficiencies of the methanol plant, and using an efficiency of 0.4 for the methanol fuel cell vehicles, it is found that the maximum allowed CO_2 in the electricity is 127.832 g CO_2 pr. kWh, as explained in section 4.3.3.

This is used as a maximum for the yearly average CO_2 content of the electricity used for the plant. The way it is done in the analysis is that an hourly CO_2 limit is defined as a user input, which sets a maximum hourly CO_2 content for the electricity. If electricity comes from a *behind the meter* solution, a new CO_2 content for the hour is calculated taking into account the volumes obtained from the wind and the volumes obtained from the electricity grid. If the CO_2 content of the hour is above the hourly limit, then the electrolyzer is not allowed to run. The hourly limit is adjusted up or down until the average CO_2 content of the used electricity by the plant is below 127.832 g/kWh. The effect of the hourly marginal CO_2 limit can be seen in Figure 6.4. The NPV is very low for low marginal CO_2 limits due to it needing a very large hydrogen storage.

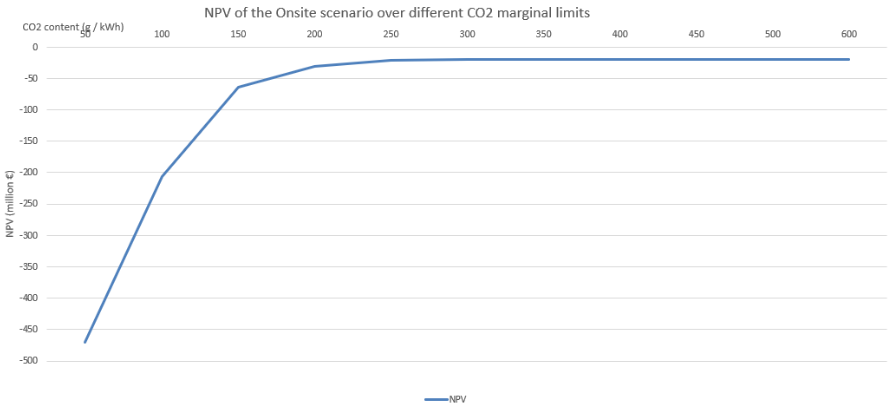


Figure 6.4: NPV in millions of euros displayed for increasing marginal CO_2 limits for the Onsite scenario. The used value in the scenario is 600 g / kWh, as the associated CO_2 savings are still above 60 %.

Taking this maximum average CO_2 content into account, the next step is to define the scaling between the electrolyzer and the methanol reactor. Given that the total electricity capacity of the electrolyzer and reactor is fixed, a smaller electrolyzer/reactor ratio means that more methanol is produced throughout the year. On the other hand, it provides less flexibility to turn the electrolyzer on and off. Different ratios can be tested to determine which combination of ratio and storage size yield good results.

The storage size is calculated automatically by looking into the maximum storage need for storage throughout the year. In addition to that, the storage minimum content was set at 10 % to ensure the storage is not empty at any given time. A 20 % storage size margin was also added as a precaution.

The electrolyzer to methanol ratio is a parameter that is very intertwined with the hydrogen storage needed and the yearly CO_2 savings. If the ratio is lower, a larger hydrogen storage is required and more CO_2 is saved, as the yearly methanol production is higher; if the ratio is higher, the need for hydrogen storage decreases and the yearly CO_2 savings drop. These phenomena can be seen in Figure 6.5, where the highest IRR for the Onsite scenario is with a ratio of 1.1, while for the Offsite it is 1.5. Considering that for the results of both scenarios to be comparable they should have the same investments and therefore the same ratio, an average ratio of 1.3 was chosen. This ratio is then applied to all the scenarios and sensitivity analysis throughout the model.

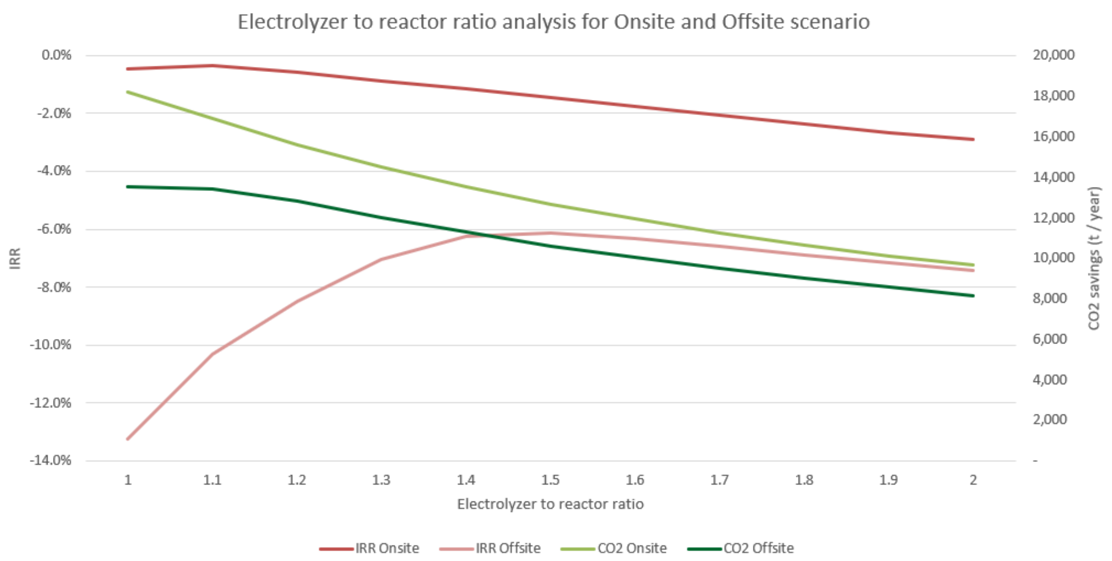


Figure 6.5: IRR and yearly CO_2 savings for different electrolyzer to methanol reactor ratios for the Onsite and Offsite scenarios.

Additionally, to the two weeks of planned outage due to maintenance, an additional week without production was added since the value of production from this week did not surpass the cost of adding the extra storage required. This enabled a total of 6317 running hours for the alkaline electrolysis. The effects on the storage content for a year is shown in Figure 6.6.

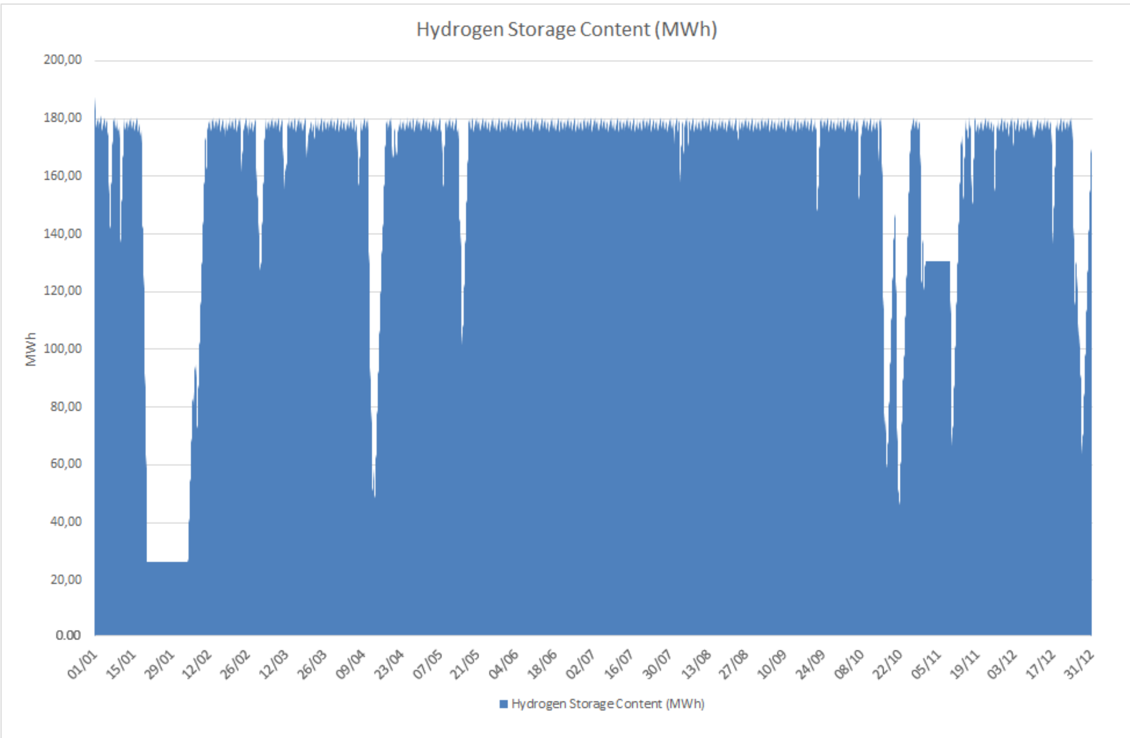


Figure 6.6: Yearly display of hydrogen storage content, when the operation is limited to a maximum CO_2 content.

In Figure 6.6 the two periods of shutdown can be observed on the hydrogen content when the storage neither increases or decreases. It can also be observed that in large blocks within the year the electricity CO_2 content is so low, that hydrogen storage never depletes more than a tiny fraction of the maximum storage content. A cut out showing the production provides a better illustration of how the production operates and can be observed in Figure 6.7. This weekly presentation in Figure 6.7 shows how the production is affected by the hydrogen storage content and the CO_2 content of the electricity.

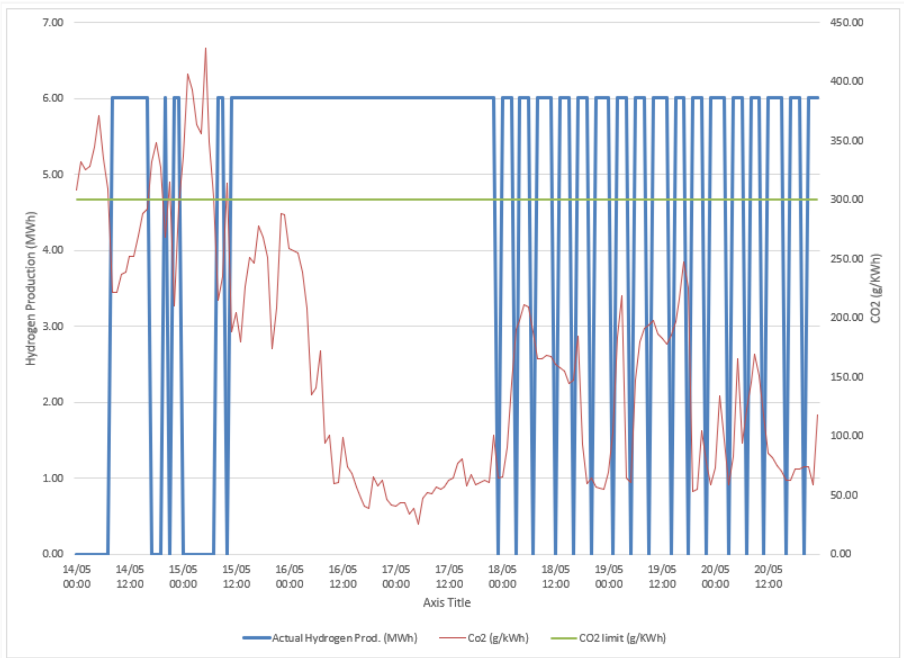


Figure 6.7: Example of weeks operation of the plant. The green line indicates the absolute maximum CO_2 content allowed in the electricity, the red line shows the actual value of CO_2 in the electricity and the blue shows hydrogen production.

As seen in Figure 6.7, in this mode the hydrogen production fluctuates back and forth after 18/05 00:00. This happens when the hydrogen storage content reaches full capacity and the electrolyzer shuts down. This indicates that an additional price optimisation can be implemented whenever the storage content allows it to happen. This price optimisation is implemented to ensure a lower production cost. To design this price optimisation, a list of preconditions were determined, which are as listed below:

- The price optimisation cannot limit the hours of hydrogen production to a point where it also limits the methanol production.
- The price optimisation cannot override the CO_2 limitation to the production hours.
- The price optimisation has to be implemented to the current setting, meaning that the model is only able to predict the electricity price one day ahead when planning production.

The price optimisation is applied to days where the initial storage content is above 75% of the total capacity. The 75% was chosen because it would allow the flexible operation to avoid running the electrolyzer in the hours of highest electricity price within the day.

At the same time, it makes sure it has enough storage content to supply the methanol reactor if the electrolyzer is unable to operate. For an electrolyzer to methanol reactor ratio of 1.3 : 1, the price optimisation determines the most expensive 7 hours block in the day to shut down the electrolyzer. The effect of this optimisation on the yearly storage content is seen in Figure 6.8 and a cutout showing the same period of time for the production as that shown in Figure 6.7 now with a price optimisation is shown in Figure 6.9.

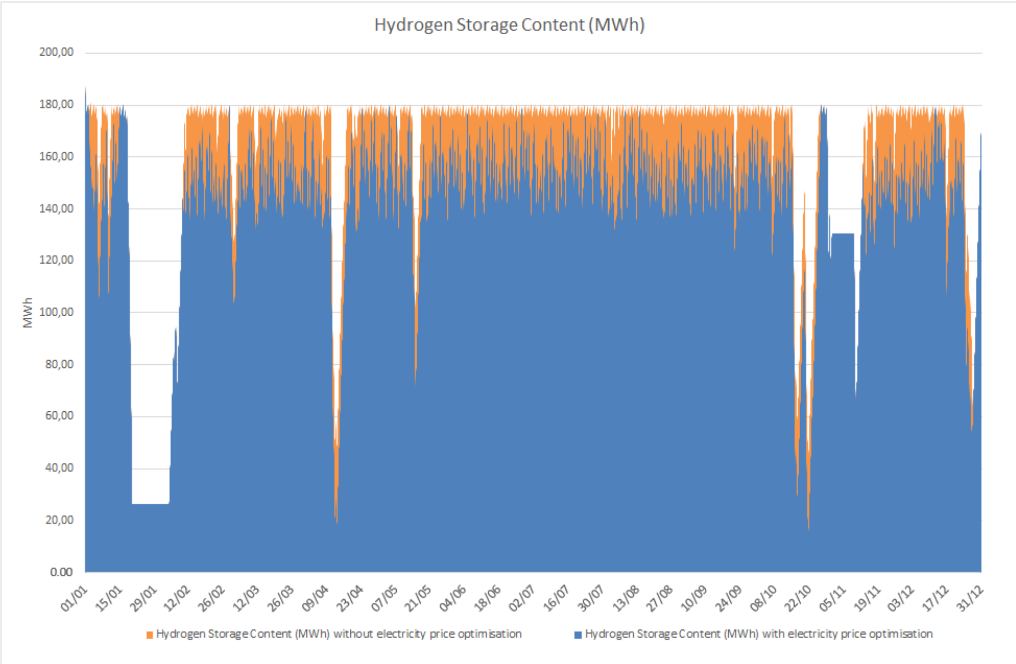


Figure 6.8: Yearly display of hydrogen storage content, when the operation is limited to a maximum CO_2 content and also use electricity price optimisation.

When comparing Figure 6.8 with the original storage content shown in Figure 6.6, it is now observed that the fluctuations in the content in the periods of almost full storage appear more random than originally. This shows that it now adjusts its production according to the operation of the plant also adjusts according to the price of electricity as well as the CO_2 content of the electricity. This can also be seen in Figure 6.9, where the production now is collected in blocks to fit the lowest production price.

To sum up, to enable flexibility in the plant and produce electrofuels that could go under the definition of biofuels, the scaling between the methanol reactor and the alkaline electrolysis and a suitable hydrogen storage is determined. After implementing this, the operation pattern is fitted to operate at the lowest electricity cost, while also considering the previously mentioned CO_2 content of the electricity and ensuring stable operation of the methanol reactor. Also, the storage is assumed to start the year full and end the year full as well. The following section presents the choice of capacity of the plant that would fit in a danish content, and lastly, these values can be used to determine the cost and incomes of such an electrofuel plant.

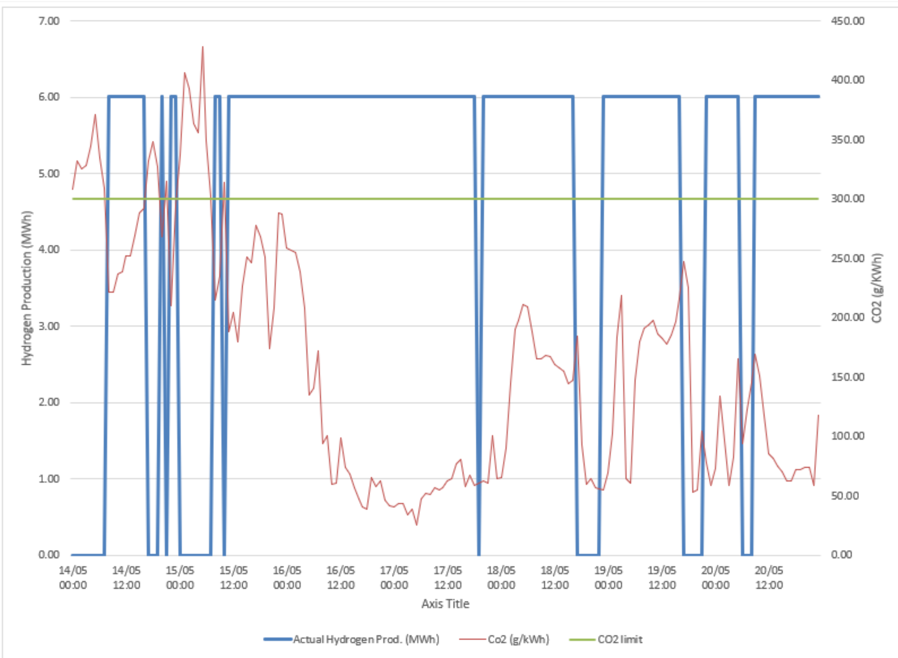


Figure 6.9: Example of weeks operation of the plant with electricity optimisation. The green line indicates the absolute maximum CO_2 content allowed in the electricity, the red line shows the actual value of CO_2 in the electricity and the blue shows hydrogen production.

6.2.3 Fitted Capacity

The sizes of the largest PtX demonstration projects conducted or currently planned in Denmark span over a size from 1 MW at the *HyBalance* project at Hobro to 20 MW at the *HySynergy* project planned in Fredericia, why the PtX plant modelled in this project is within this range. Generally speaking, the larger you build a facility the lower the investment price pr. MW capacity will be. This scaling effects can also be considered when the size of the built PtX plant is to be determined. Additionally, larger capacities of the plant require added electricity infrastructure which potentially results in a cost for society but this is not addressed in this project. To fit within the current capacity of the PtX projects and to fit within the limitations of the data used for modelling the plant, a capacity of **10 MW** is determined for the modelled plant. Another very important factor in the scaling is the amount of CO_2 available at the biogas plant, as it limits the amount of methanol that can be produced at a location.

Using a 10 MW electrolyser, the corresponding values for the methanol reactor and hydrogen storage can be determined from the CO_2 content profile of the electricity based on the year 2019. Specific values for the four tested scenarios is shown in table A.1 and A.2 in Appendix A.

6.2.4 Operating Decision Steps

The previous subsection explained the calculation methods and criteria applied to the plant model. The objective of this subsection is to relate them to each other in a step-like manner so that it becomes clear how the model works. The steps used are presented in Figure 6.10.

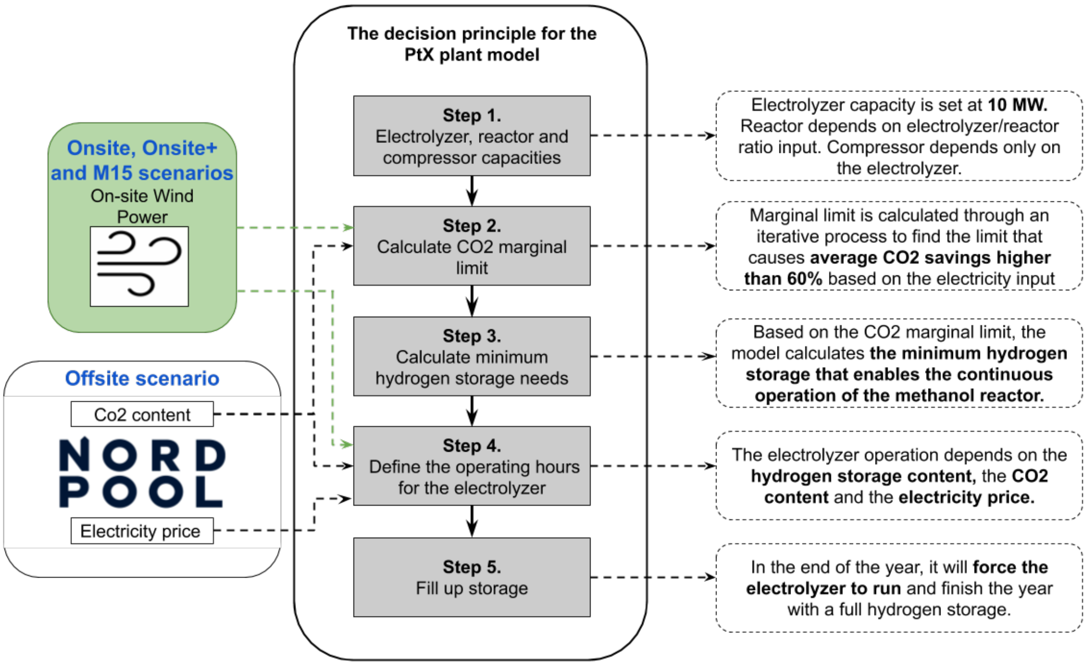


Figure 6.10: The decision principal behind the excel model and representation of how the two scenarios for *On-site* and *Off-site* are impacting the model.

6.2.5 Scenarios

Based on the various step and considerations for the plant design four scenarios are investigated which also are outlined in section 4.3.3 on page 48. The inputs in the model for these four scenarios vary as displayed in Table 6.6. Based on these inputs, other numbers that are calculated and used throughout the scenarios can be seen in Appendix A.

Element	*Offsite*	*Onsite*	*Onsite+*	*M15*
CO_2 Marginal Limit (g/kWh)	234	600	600	191
Wind behind-the-meter (MW)	0	20	20	20
Engine efficiency	40 %	40 %	40 %	20 %
Heat Sales	50 %	50 %	100 %	50 %
Oxygen Sales	0 %	0 %	100 %	0 %
Engine change (€ / vehicle)	3 000	3 000	2 000	0

Table 6.6: Different inputs used for the different scenarios.

6.3 Scenario Results

The results of the different scenarios are presented, compared and discussed in this section. For these scenarios, the cash flow and NPV are presented in Figure 6.11.

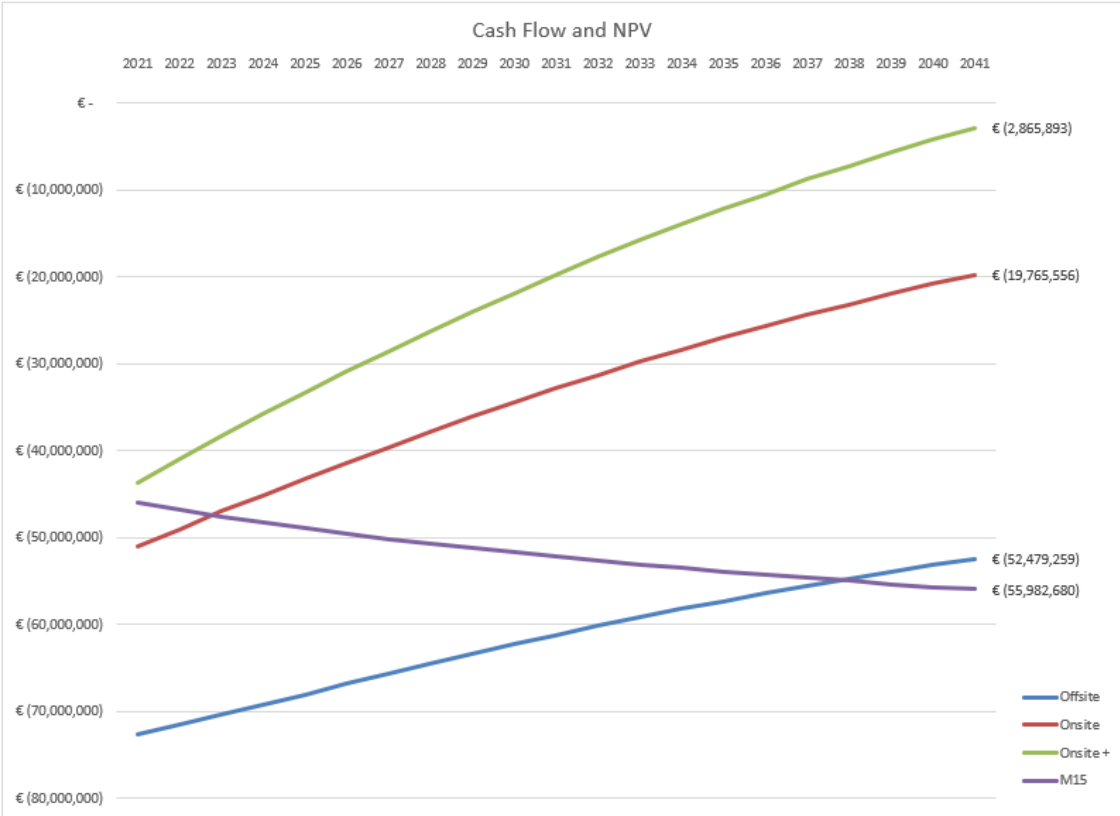


Figure 6.11: Cashflow and NPV for the scenarios.

From Figure 6.11 it is seen that while none of the scenarios are able to achieve a positive NPV, the difference between the different scenarios spans between approximately negative 3 million euro and negative 56 million euros. This indicates that some applications of the PtX plant and the produced methanol are more favourable to others, from a socioeconomic point of view. The *Onsite+* scenario is seen to give the lowest loss, whereas the *M15* is seen to have the worst business case. Additionally, it is observed that in the scenario *M15* the production costs exceed the potential revenue of the plant, therefore negating the business case as the years go by. Despite the scenario *Offsite* having the highest investment price more than 50% higher than that of the *M15*, the NPV is still seen to be higher. These points shows that using the methanol in a petrol mix gives a worse NPV for the plant, than using it in methanol fuel cells.

To further investigate the differences between the four scenarios, Figure 6.12 presents a detailed comparison between the revenue breakdown in each scenario. This figure differentiates between the revenue in the year 2022 and the year 2030, since the electricity grid is assumed to be 100% renewable by 2030, in accordance with the goals of the Danish Government outlined in 1.2 on page 4.

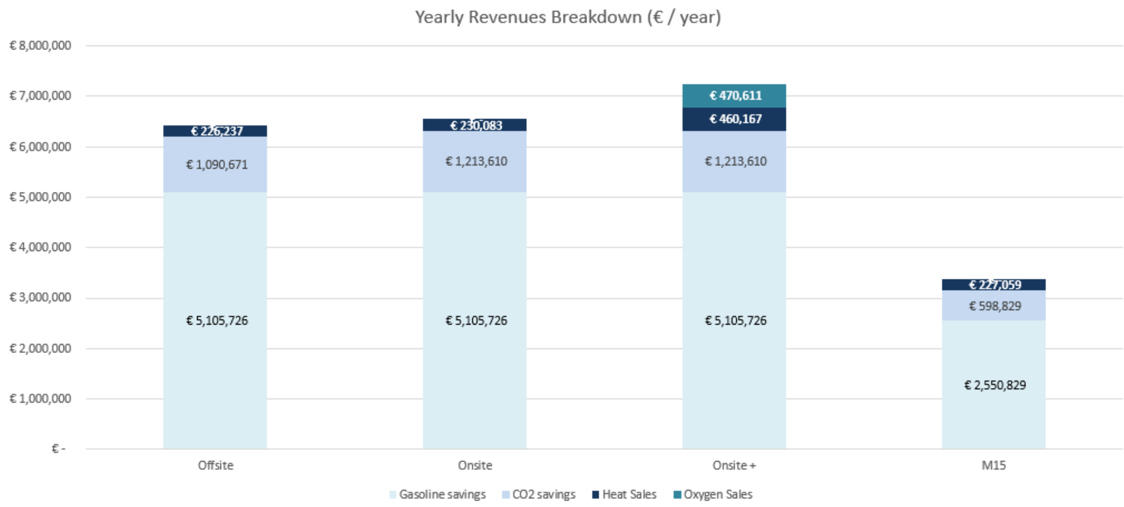


Figure 6.12: Revenue breakdown of the different scenarios.

Figure6.12 also shows the different revenue streams of the different scenarios. Here the revenue from replacing gasoline with methanol is presented as *Gasoline savings*. It is noticeable that the *M15* scenario has an income from *Gasoline savings* and CO_2 *savings* corresponding to half of what is in the other scenarios. This can be explained by the efficiency of the fuel use is half that of the other scenarios, due to it being used in a combustion engine. The difference between the *Offsite* and *Onsite* is here mainly seen to a small increase in CO_2 savings and heat sales in the *Onsite* scenario. The electricity of the *Onsite* scenario has a lower CO_2 emission content than that used in the *Onsite*, why the CO_2 savings and number of production hours are higher, the last-mentioned increasing the production of heat and with that the revenue from heat sales.

The *Onsite +* scenario, which was also seen to have the highest NPV value, can see to have twice the income from heat sales compared to the other scenarios. It is also seen that the potential yet optimistic revenue from oxygen sales is higher than that of the heat sales, therefore indicating that the oxygen sales can have a significant impact on the profitability of a PtX plant. The cost breakdown of the yearly operation expenses of the four scenarios can be observed in Figure 6.13.

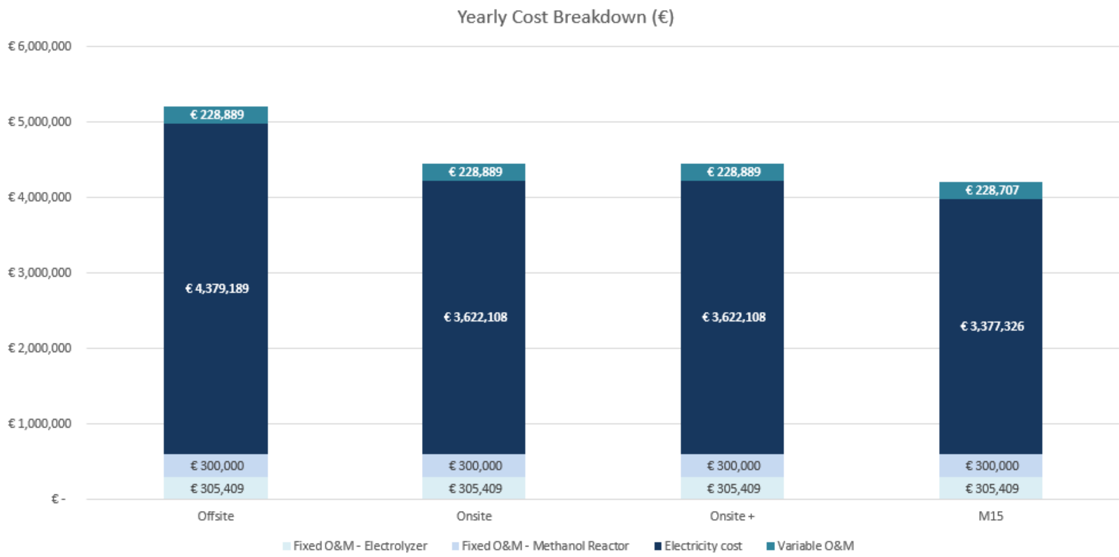


Figure 6.13: Cost breakdown of the four scenarios.

In Figure 6.13 the only significant cost difference is that of the electricity from scenario *Offsite* and all the other scenarios. Since the other scenarios use an *Onsite* type production, it can be deduced that the added expenses must account for added tariffs paid to the grid. The lowered electricity cost seen in scenario *M15* can be explained by a small decrease in production hours, compared to the other scenarios.

Lastly, the Investment cost breakdown is shown in Figure 6.14 which shows the various investment cost of the different component for the PtX plant in all scenarios. Since the same capacity for the electrolyser and methanol reactor are used throughout all scenarios, this is seen to remain the same. In the scenarios using fuels cells, *Offsite*, *Onsite* and *Onsite +*, it is seen that the investment cost of changing the engine accounts for 31-43% of the total investment cost, therefore making it a significant part of the total investment. Despite the *M15* scenario not having to account for the investment to the engine replacement it is still seen that the needed storage size and cost of this, increase the investment making it only the second cheapest scenario. The high storage requirement can be explained by the limited production hours of this scenario, forcing the plant to stock up on hydrogen whenever the CO_2 content of the electricity allows for it. The same effect is seen in the *Offsite* scenario, which uses the raw CO_2 content profile of the electricity grid thereby also having to produce more when the electricity is favourable. The small decrease in car engine change when comparing *Onsite +* to *Offsite* and *Onsite*, is due to the *Onsite +* using a lower price pr. engine change than the other scenarios as to function as a more optimistic scenario.

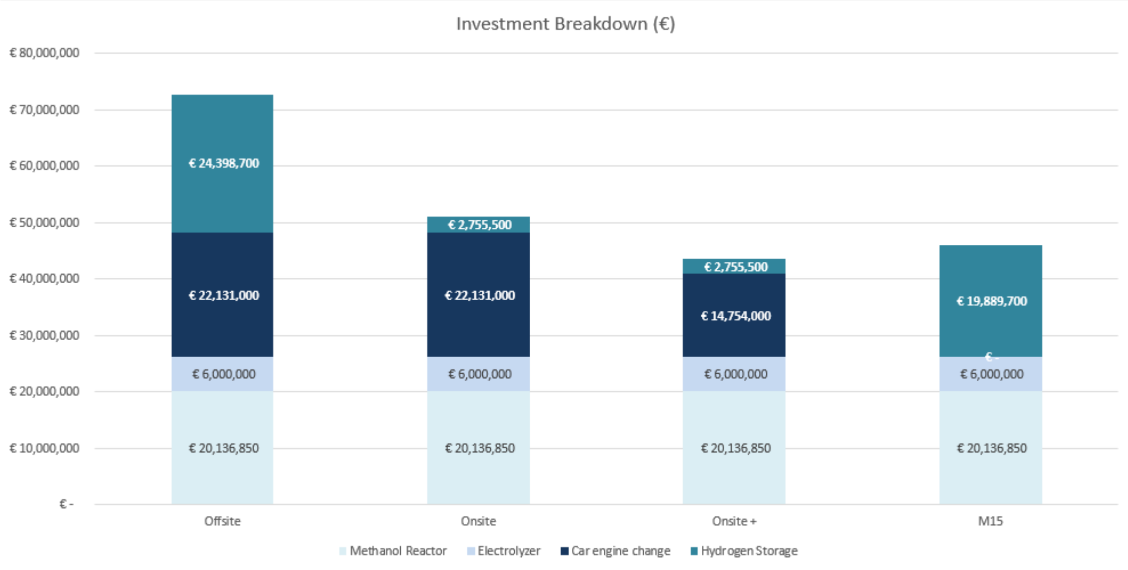


Figure 6.14: Investment breakdown of the different scenarios.

Other significant values for the four scenarios can be seen in table 6.7. In this table, the methanol price indicates the minimum methanol price required for achieving an NPV of zero within the lifespan of the designed PtX plant. It can be observed that the socioeconomic cost of producing the methanol observed in table 6.7 are higher than the methanol from fossil fuels at 225 €/t, 400 €/t of bio-methanol and 500-600 €/t for methanol from electrolysis (Jensen 2020).

Scenario	***Offsite***	***Onsite***	***Onsite +***	***M15***
NPV (million €)	-52.47	-19.77	-2.87	-55.98
IRR	-7.0 %	-0.9 %	3.3 %	No returns
No. Cars Retrofitted	7 377	7 377	7 377	0
CO_2 savings (t)	11 984	14 492	14 492	6 031
Methanol price (€ / t)	1 343	983	796	1 000
Electrolyser operation hours	6 295	6 295	6 295	6 295

Table 6.7: Sum-up of the two scenarios, showing NPV, CO_2 savings and the yearly operation hours of the electrolyser. The methanol price presented is the *break-even price*, meaning that this is the required minimum price required for the methanol plant to earn itself within the lifetime of the plant.

Based on the results presented in table 6.7 and the data shown in the four previous graphs, the following conclusions can be drawn:

- The *Onsite +* scenario NPV is considerable better than the other scenarios.
- Based on the methodology presented in this report a methanol mix solution as presented in scenario *M15* is not viable from a socioeconomic perspective, and should not be further investigated in this context.
- Combining the PtX plant with a capacity of wind turbines *(Onsite)* increases the possible production hours and decreases the investment cost requirements of the hydrogen storage.
- This combination also decreases the cost of electricity grid tariffs, thereby decreasing the operation costs.
- The revenue from heat and oxygen has a potential of accounting for 13% of the revenue in the most favourable scenario presented.

Despite the NPV of scenario *Onsite+* being the most promising, the results from this scenario might be questionable due to the relatively high income from heat and oxygen sales. Since the analysis is supposed to give a general estimation of socioeconomic benefits of PtX in Denmark, elements that require individual considerations, such as proximity to district heating and potential oxygen buyers, are not taken into account in the *Onsite+* scenario. Based on this the scenario *Onsite* is considered more suitable since the income of the heat is fitted to only include used in the biogas plant which acts as the CO_2 supplier, thereby decreasing the heat transportation distance. The oxygen sales are not included in this scenario either, due to sales potential and distances being considered individually for each plant. The value streams of the *Onsite* scenario can be seen in Figure 6.15. Due to these considerations, a sensitivity analysis is conducted on the plant type described in scenario *Onsite* to estimate the effects of various influences on the results, and to clarify potential pathways for PtX. For the *Onsite* scenario, the NPV was -0.9 %, meaning that an interest rate of -0.9 % would have to be used to make the NPV be 0. For this reason, even if a sensitivity analysis on the interest rate was conducted, all values above 0 % would result in a negative NPV.

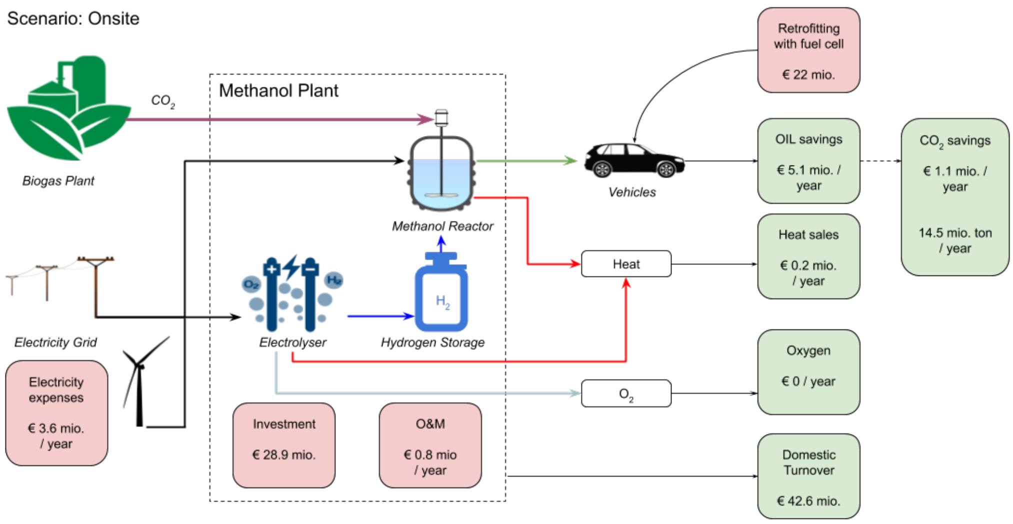


Figure 6.15: Visual representation of the value streams present in the Onsite scenario.

6.4 Sensitivity Analysis

The *Onsite* scenario is used as the selected scenario for the sensitivity analysis, due to it being a better representative of an average plant with an onsite solution. The NPV has been chosen as an adequate indicator for the feasibility of plant design. If the NPV is greater than 0, it is feasible. Firstly, each sensitivity parameter is outlined and addressed in relation to uncertainties. Secondly, each sensitivity parameter is varied with -/+ 20 % to assess which parameters are the most sensitive in the plant design to a percentage variation. This is used as a preliminary analysis to indicate the robustness of the economics plant design case to each parameter. However, the range that each parameter can vary is different for each parameter; therefore, a second investigation is carried out in which a more adequate and feasible low and high range of each parameter is used. Combining the knowledge from these two outputs make it possible to have a better overview of the effect of each parameter in the NPV of the feasibility study in relation to reality.

Gasoline price

In all of the scenarios, the gasoline savings represent a revenue to the analysis. Historically the gasoline price has been constantly changing (Trading economics 2020) . To test this effect the gasoline price is varied with +/- 20%, and the effects on the NPV is presented.

Climate effects (CO_2 price)

As discussed in Chapter 4.1, section 4.3.3, the method of valuing the environmental effects of transforming the transportation sector from fossil fuel to methanol is by using the social price of mitigating action by 2020. It represents the value needed for mitigating the CO_2 emissions on a global scale. However, the actual value used by Denmark could be different. The Climate Council (Klimarådet 2020*b*) suggests that for socioeconomic cases used to investigate public projects, the price of CO_2 should be in the proximity of 1500 DKK/ton CO_2, roughly corresponding to 200 euro/ton CO_2. Opposite, if a CO_2 avoidance income were to be directly applied in the current framework the value used would more likely be that of the current CO_2 quota price at approximately 25 euro/ton CO_2, as set by the European Union Emission Trading Scheme (EU ETS). The sensitivity analysis includes both of these to see the effects on the NPV of the PtX plant.

Heat sales

The PtX plant has an excess heat from its production corresponding to 25% of the energy input (Danish Energy Agency 2017). This is however deemed to be of low quality, meaning that the utilisation within current district heating systems would require and additional heating. Moreover, biogas plants which act as a CO_2 source are generally not placed within close to the densely populated areas, where district heating is often present. Therefore, the plant analysis tests scenarios with and without an income from selling heat. The value of selling heat is assumed to be the same as the cost of producing heat using a heat pump for baseload, which is 25.8 €/MWh. As a sensitivity parameter, the value for producing heat from straw (42.8 €/MWh) and from an electric boiler (54.8 €/MWh) was used. (Niras et al. 2018) The prices is the cost without taxes but including OPEX and CAPEX covering baseload heat.

The reason to compare it to baseload heat price was that the heat generation of the power-to-methanol is somewhat constant, as the methanol reactor is operating most of the time and the electrolyzer has a high number of operating hours providing a relatively constant heat output.

Oxygen sales

In PtX applications, oxygen is a byproduct of the electrolysis process and is produced in a ratio 1:2 oxygen to hydrogen. The oxygen that comes out of the electrolyzer has a high purity and could be used in other industries. However, the cost of compressing and transporting the oxygen is very expensive which is why oxygen is usually produced next to the end-user. Therefore, the oxygen sales are a very uncertain parameter which depends on the location chosen for the methanol plant. For the *Onsite* scenario, oxygen sales are not considered as it is assumed that most of the suitable locations for the methanol plant would be too far away from an oxygen consumer. The price used for oxygen was calculated based on how much electricity is used for air distillation. This approach follows the methodology of the PowerStep Project (Lardon et al. 2018) where electricity consumption to produce 1 kg of O_2 used is 0.87 kWh/kg. Using the average spot price of 287 €/MWh and fixed costs (TSO and DSO tariffs) of 200 €/MWh, the oxygen cost becomes 0.057 €/kg.

Wind to electrolyzer ratio

When comparing the difference between the result obtained from the *Onsite* and *Offsite* scenarios it is seen that having a capacity of wind energy to supply onsite makes the PtX more profitable, by enabling more production hours while also reducing the cost of electricity grid tariffs. For the *Onsite* scenario it was chosen to have an amount of wind energy available at the site corresponding to double that of the electrolyser in the plant. Since this was seen to better the NPV of the plant, the effects of reducing and increasing this amount of wind capacity are tested. It is here chosen to increase and decrease the capacity with 50% and see the effects of doing this.

Electricity price

The electricity price is dependent on the geographical location of the plant as well as the time period chosen in the analysis. The electricity price used in all scenarios is that of DK west in 2019 with an average of 38.49 euro pr. MWh. This price is used due to this being the newest available full-year profile. The average electricity price can, however, vary depending on external effects, such as weather, why the price for the years in which the methanol plant operates varies. An example of the varying electricity price can be shown by comparing the prices for 2015 and those for 2018. Here the average electricity price for DK west was varying from 22.90 euro pr. MWh in 2015 to 44.05 euro pr. MWh in 2018, illustrating that the price can almost double in the course of just a few years. Since these prices are the yearly minimum and maximum since 2012, they are tested to see the effects on the system.

Tariffs

As the DSO and TSO tariffs together make up for approximately 41% of the total electricity price imported from the grid, their value can potentially have a large effect on the operation costs of the PtX plant. Even though it represents a high percentage of the final electricity cost, the TSOs and DSOs fees cannot be differentiated from customer to customer. At least not if delivering the same quality of security of supply. As seen in Figure 6.13, the electricity price is by far the largest cost of the yearly operation costs, and the influence of the tariff on the system should therefore be investigated. As the *Onsite* scenario does receive some of its electricity from wind turbines connected with the plant, this electricity price is without tariffs cost. The DSO tariff cost vary depending on the placement of the plant, different DSO tariff prices, to the various locations are show in Figure 6.16. To see the influence of the actual tariff of the system cost, these are changed to zero and the effect on the NPV is observed.

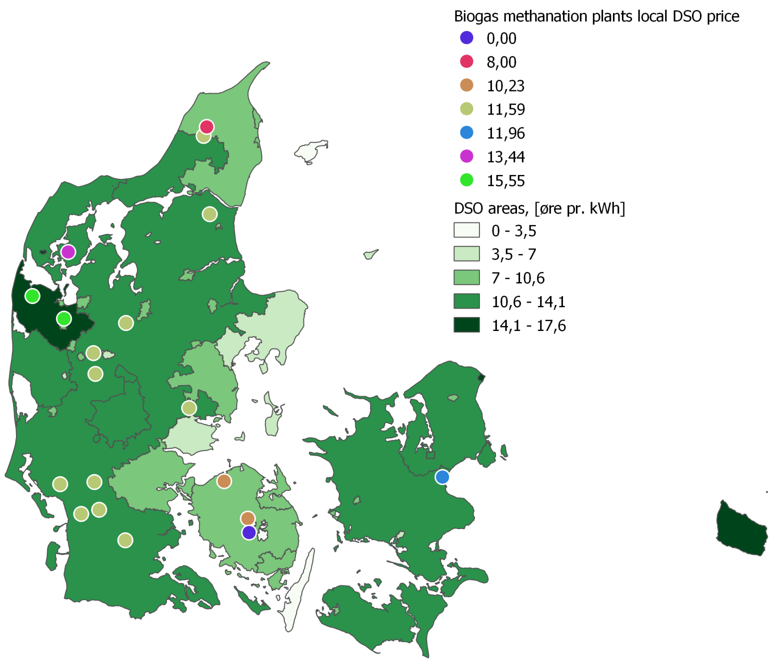


Figure 6.16: Generated Qgis map delineating the DSO's B-low tariffs (Dansk Energi 2019). The points in the map represent the potential biogas plants and the corresponding DSO tariffs (øre pr. kWh) for a 10 MW electrolyzer power-to-methanol plant. (Sustainable Energy Planning Department, AAU 2020) The biogas plants and their capacities are discussed in Section 6.6

Investment

The prices regarding the investment cost of the plant (excluding the cost of hydrogen storage) were taken from the DEA (Danish Energy Agency 2017). In this catalogue, it is mentioned that the suggested price of the methanol plant is set relatively high and that the uncertainty range would vary between 50%-100% of the price suggested for the methanol plant. Additionally, the investment price used for retrofitting the fossil-fuelled engines to use pure methanol was based on a price range where the average was used in the outlined scenarios. Generally speaking, the investment prices should be viewed as a varying range, since the technology is still in an early stage where the current development and market can have a lot of influence on the cost of this technology. To accommodate for this price range the sensitivity analysis tests the effects of reducing and increasing the total investment price of the PtX plant, with 20%.

6.4.1 Results of Sensitivity Analysis

Preliminary to testing the sensitivity of the plant using values as presented and discussed in section 4.3.3, the values of the parameters are varied between +/-20%, and the results are shown in Figure 6.17.

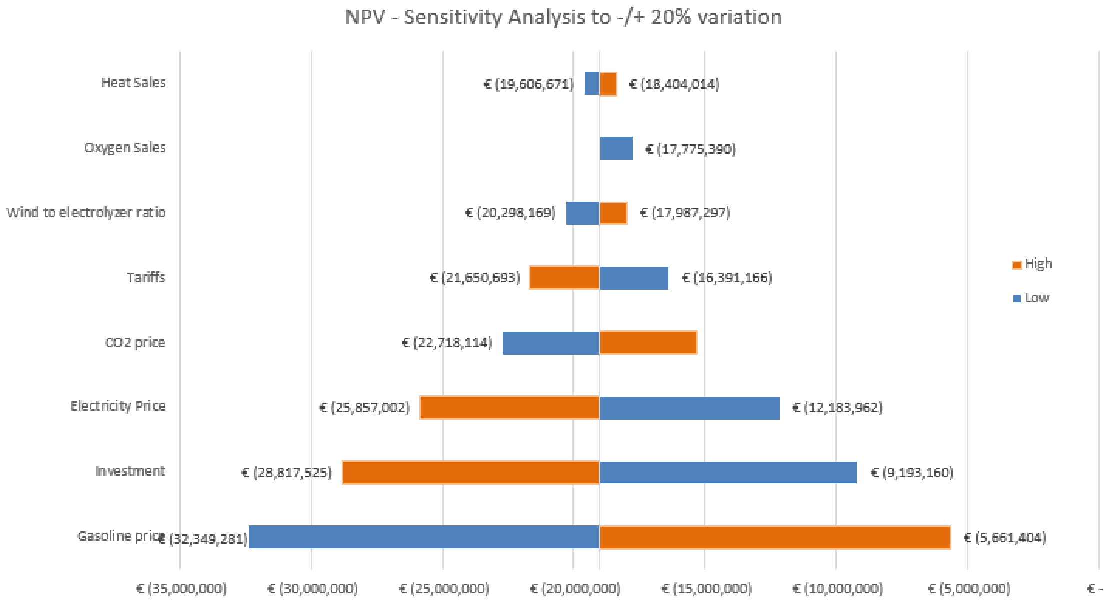


Figure 6.17: Overview of the NPV when varying the sensitivity parameters for 20 %. High represents +20 % and low means -20 %. The oxygen is added by 20 percentage points instead, as its initial value was 0 %.

Figure 6.17 shows the effects of changing the different sensitivity parameters with 20 % but the results should be viewed as a preliminary indication of the effects of the sensitivity analysis. This is done to show which elements have the highest effects on the NPV of the plant. It is seen here that the parameter *Oxygen sales* only goes from 0 to +20% of the full value of the oxygen produced. This is because the *Onsite* scenario had no income from oxygen. Given that adding 20 % to zero is still zero, it was chosen to add 20 percentage points instead. For this reason, the results from the oxygen sensitivity test can be a bit misleading when comparing to the other parameters. It is however still presented to indicate the potential for oxygen sales.

Table 6.8 shows the ranges considering of low and high values for the parameters used in the second step of the sensitivity analysis.

Parameter	**Range (-)**	**-20%**	**Onsite**	**20%**	**Range (+)**
Gasoline price (DKK / L)	€ 3.70	€ 3.70	€ 4.63	€ 5.56	€ 5.56
CO_2 price (€ / t)	€ 25.00	€ 59.20	€ 74.00	€ 88.80	€ 200.00
Heat Sales	0%	40%	50%	60%	100%
Oxygen Sales	0%	0%	0%	20%	100%
Wind to electrolyzer ratio	1	1.6	2	2.4	3
Average Spot Price (DKK / MWh)	172.2	229.6	287.4	344.4	330.05
Tariffs	0%	80%	100%	100%	50%
Investment	80%	80%	100%	120%	120%

Table 6.8: Inputs used in the sensitivity analysis deemed as a possible range from low to high.

Figure 6.18 presents the results of the sensitivity analysis using the values for the parameters, as discussed through the section, and summarised in Table 6.8. The figure shows the inputs regarded as more feasible in the current reality. The highest change in the NPV is of the CO_2 price variation, due to the high degree of uncertainty regarding which price will be used in the future. The electricity price is the second parameter that could increase the NPV when using 2015 spot market prices. However, 2015 was an unusual year with very low electricity prices and it is unlikely that the spot market price would be maintained at that level throughout the 20 years lifetime of the plant. The third one is the gasoline price, closely followed by the tariffs. The other parameters have a lower impact on the NPV when compared the 4 parameters mentioned. The revenue from the oxygen sales appears to be much higher than the heat sales, but it is because the heat sales are considered to be already 50 % of the maximum in the Onsite scenario. The variation on the heat sales is of 50 percentage points while it is of 100 percentage point for the oxygen. Lastly, it can be seen that the wind capacity to electrolyzer ratio has a non-linear effect on the NPV. The difference in NPV is higher when changing from 2:1 to 1:1 than changing from 2:1 to 3:1. This is because there is a limit to how much electricity that can be utilized at the plant.

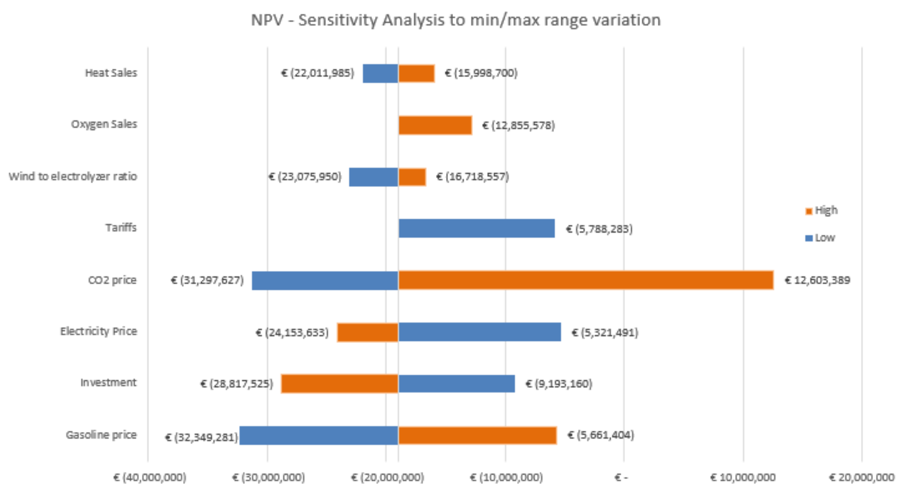


Figure 6.18: Overview of the NPV when varying the sensitivity parameters for the range deemed possible shown in 6.8.

Employment effects

As described in subsection 4.3.3 on page 49, the methodology used to measure the employment effects followed the one used in the Ida Energy Vision 2050 (Mathiesen et al. 2015). The changing from fossil fuels to power-to-methanol means that more money stays within Denmark, as the import share of oil products is higher than the investment and electricity costs. The added funds are then considered to generate turnover and generate jobs. The import shares of the different elements that compose the OPEX and CAPEX of the power-to-methanol business case can be seen in table 6.9.

Parameter	Import share	Amount (€)
Investments*	40 %	30 614 009
Operation & Maintenance	20 %	667 438
Fossil Fuels	10 %	-510 572
Tariffs	40 %	744 591

Table 6.9: Inputs used in the job creation analysis to determine the domestic turnover effect. The import share values are obtained from (Mathiesen et al. 2015). *The investment turnover is considered only 1 time in year 0.

The investment amount is only considered in the first two years, while the O&M, the tariffs and the gasoline import turnover effect are considered from the 20 years operation period. By adding these up, the total sum is equal to 42.7 million euros. Dividing it by 22 years (2 years construction + 20 years operation) and using 1 million euros equals to 15 FTE (full-time employment), it is equivalent to 29 jobs throughout the 22 years. If looking at the OPEX and CAPEX separately, it is equal to 230 FTE in the first 2 years, then 9 full-time employment throughout 20 years.

6.5 Pathway of PtX

As seen throughout the previous section 6.3, the profitability of the PtX plant is non-existing in all scenarios and is only achievable by increasing the revenue from CO_2 avoidance or by having a combination of the changed elements as presented in the Sensitivity analysis. The *Theoretical Framework* in Chapter 3 presents the overall consideration of transitioning a system which can be exemplified in this report from substituting fossil fuels in the transportation sector with electrofuels. This change is considered a radical technological change at the system level and in order to enable this the theory of choice awareness has been considered for the proposed alternative together with assumptions from an innovative democracy view on institutions and markets. The stakeholder investigation and the energy system analysis outline important aspects relevant for the development for PtX in the Danish context and the related system. The various changed sensitivity parameters are all part of this system and can at the organisation level be influenced as described in Figure 6.19.

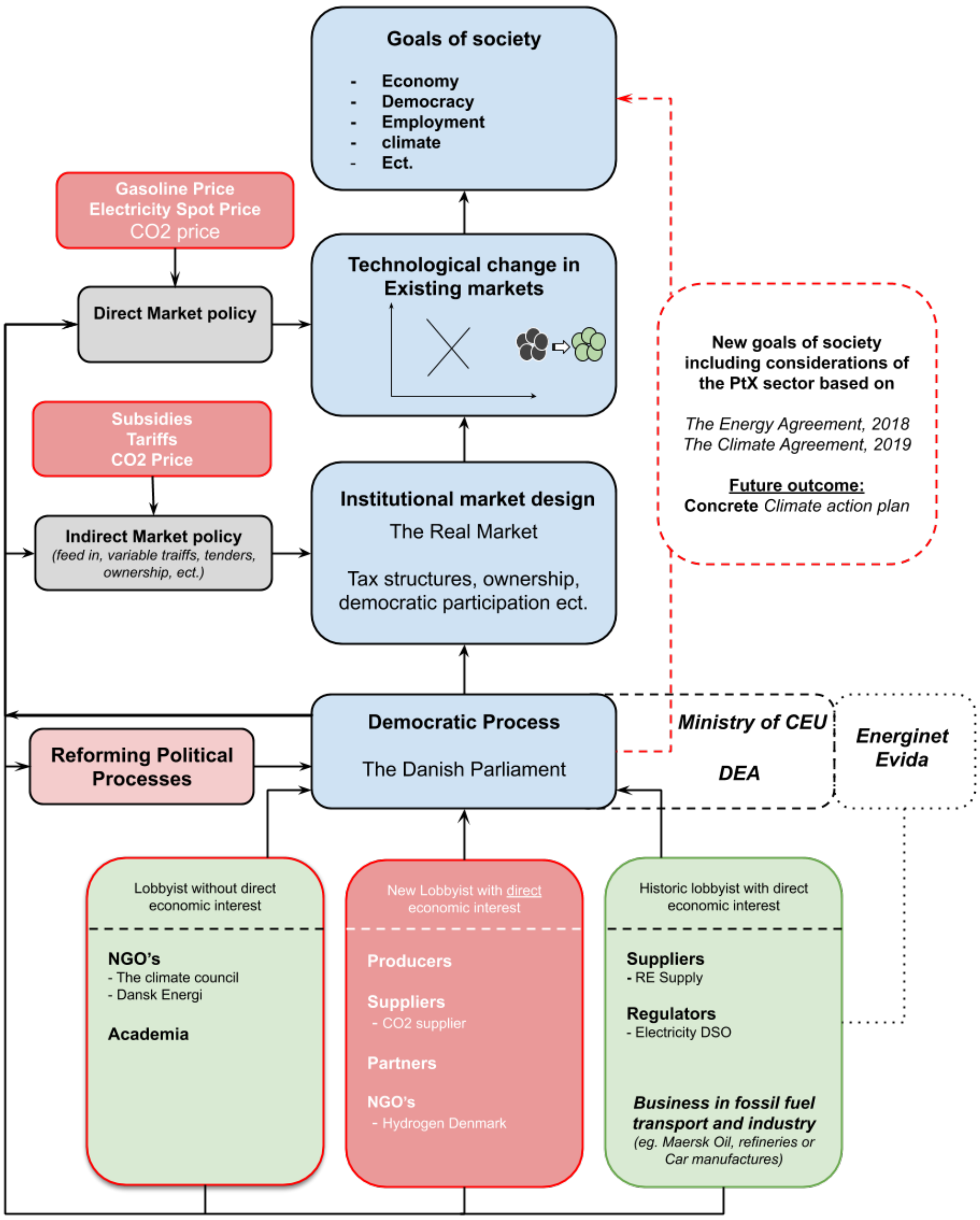


Figure 6.19: Innovative democracy system description, showing emphasis of pathways to impact some of the sensitivity parameters tested in the sensitivity analysis. This is presented together the results from the stakeholder analysis as presented in figure 5.2 on page 62

Figure 6.19 shows that potential pathways of implementing some of the tested sensitivity parameters are either through Direct- or Indirect -market policy. Here the sensitivity parameters; *Heat sales*, *Oxygen sales* and *Wind to electrolyser ratio* were excluded from the figure due to them being mostly dependent on the proximity to buyers, rather than market policies. This does not mean that some specific indirect or direct market policies could not affect the feasibility of selling the various byproducts from the PtX plant, but in this project, it is not considered further since the external effects are estimated to make it impossible to give a uniform value that can be applied generally for PtX plants.

The parameters *Investment*, *Tariffs price* and CO_2 *price* are all located under **Indirect Market policy**. The **Indirect Market policy** can here enable special exclusion from tariffs, promoting CO_2 avoidance by subsidising it and supporting technology development by funding PtX plants, thereby developing the market towards accommodating the production of electrofuels. The *Direct Market Police* is seen from Figure 6.19 to be able to affect the *Gasoline price*, the *Electricity spot price* and again the CO_2 *price* as also seen affected by **Indirect Market Polices**. **Direct Market Policies** are policies such as CO_2 quota prices which are currently controlled by the EU ETS and account for the supply and demand of fossil-based energy. If the EU ETS restructured their quota value to be more in accordance with the price of actual climate change mitigation actions this would automatically increase the value of carbon capture and utilisation, which the designed PtX plant in this report is doing. This quota price increase could potentially also affect the electricity production price as well as the price of fossil fuels such as gasoline and thereby improve the feasibility of the PtX plant.

Changes in the parameters outlined in the sensitivity analysis such as the CO_2 price, electricity price and tariffs could increase the feasibility of the socioeconomic study. This could create a pathway to transition towards electrofuels in the transportation sector from a socioeconomic point of view.

6.6 Potential Capacity in Denmark

In the analysis it was found that producing methanol from one PtX plant, for the transportation sector, has the potential of saving 14 492 tons of CO_2 yearly for a 10 MW capacity electrolyzer plant. This is however only a small fraction of the total CO_2 emissions from the transportation sector, which is approximately 12 million tons CO_2 yearly as presented in Figure 1.4 on page 7. This section investigates how many biogas CO_2 sources the investigated plant design can be applied to in the Danish context, and outlines what the maximum Power-to-methanol capacity is. From the *Energy Maps* (Sustainable Energy Planning Department, AAU 2020) the *Biogas Methanation Sources* are displayed in the danish context which in this report is used as an index of the potential CO_2 sources of Denmark. The methodology used to make the maps can be seen in the article by Nielsen et al. (Nielsen 2020). The size distribution and quantity of biogas CO_2 sources relevant for an upscale of the designed PtX can, therefore, be conducted through extraction from this page as in Figure 6.20.

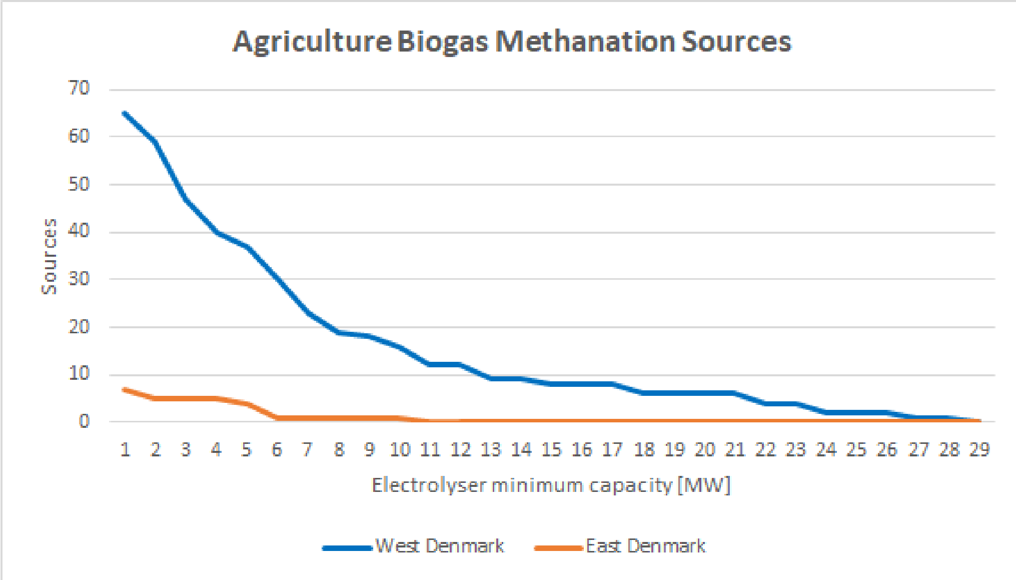


Figure 6.20: Size distribution for the agricultural CO_2 sources in Denmark.

In Figure 6.20 the electrolyser capacity is presented as a measure of indicating the potential of the CO_2 source. This is to be understood as the electrolyser capacity belonging to the Power-to-methane plant that can be attached to the biogas plant. Since Power-to-methane and power to methanol require the same amount of CO_2 input it is assumed that this number can be directly transferred for the case presented in this project. The graph presented in Figure 6.20 does however not account for the scaling between the electrolyser and methanol reactor, that was used for the plant design, to create flexibility in the production. This scaling was 1.3 sizes bigger of an electrolyser, and this means that in order to find the amount of appropriate CO_2 sources, an electrolyser capacity of 7.7 is used. It is here observed from Figure 6.20 that 21 sources can fit with that electrolyser capacity, where one is in East Denmark and 20 are in West Denmark. The exact placement of these different CO_2 sources is shown in Figure 6.21.

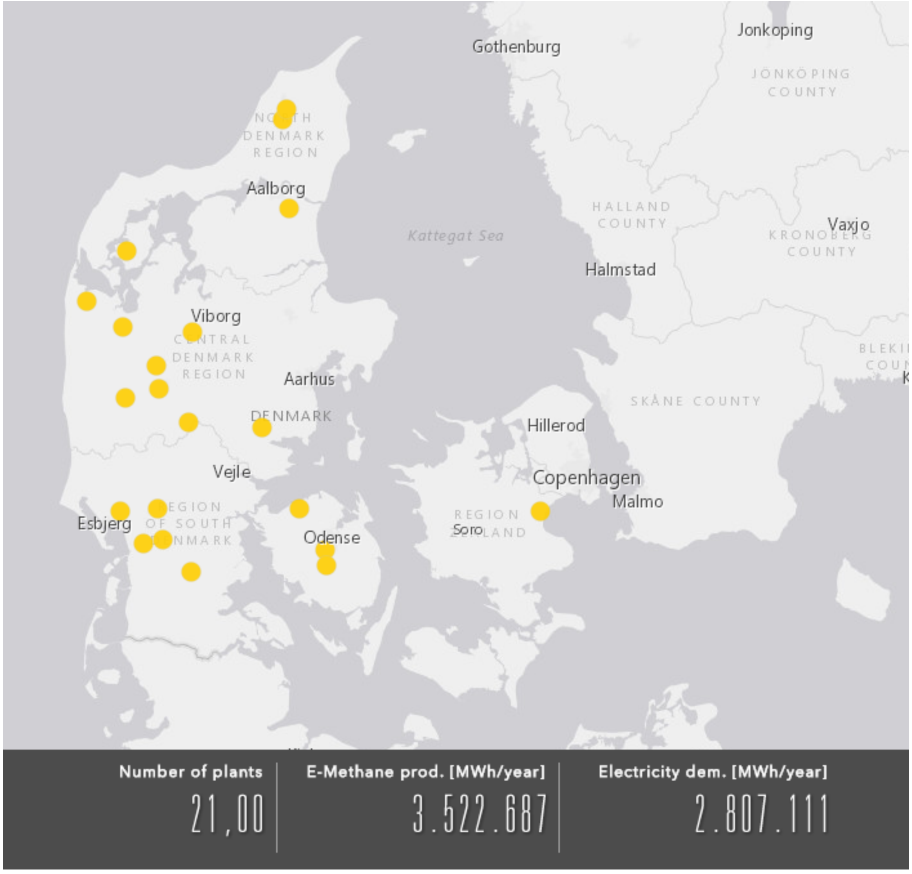


Figure 6.21: CO_2 sources containing the required amount for a 10 MW plant using the scaling of 1.45. Cut-out from from *Energy Maps*(Sustainable Energy Planning Department, AAU 2020)

Out of the 21 plants displayed in Figure 6.21, 14 contains gas injection upgrades, meaning that the CO_2 source purity is acceptable to be used directly in the methanol plant. All of these 14 plants are placed in DK West, meaning that the electricity price used for the plant design will be adequate in estimating their operation costs. Therefore, if the CO_2 capacity of these 14 plants was used, it would would result in enough methanol production to be used by 103 278 personal vehicles, creating CO_2 savings of 202 888 ton CO_2 pr. year. If the remaining 7 biogas plants were upgraded and used for methanol production these numbers would increase to 154 917 personal vehicles and a CO_2 saving of 304 332 ton CO_2 pr. year.

Lastly, if the methanol plants were fitted to optimise its production to include all CO_2 emission from the biogas sources displayed in the *Energy Maps*, the capacity would correspond to that of 40 methanol plants. This would result in 296 998 personal vehicles using methanol instead of petrol creating a CO_2 saving of 583 448 ton CO_2 pr. year, corresponding to 4.8% of the total emission of the Danish transportation system. Here the biogas upgrade is not limiting the used sources.

7 Discussion

In this chapter, the theories and methods used for structuring the analysis in the projects, along with the execution of these analyses, are discussed. This is done to present how these can have affected the results of this project and to present on which grounds the conclusions of the project can be drawn. The chapter is divided into four sections, discussing the theory and methodology, the stakeholder analysis, the energy systems analysis and lastly summarising the conclusions that can be drawn together from these discussions. The following section presents a summary of the sub-questions and go through how these were answered through the project. Following this summary, the discussion is presented from section 7.2.

7.1 Sub-question Summary

To answer the problem formulation a list of sub-questions has been formulated. Throughout this master's thesis report, these different sub-questions have been answered using various analysis based on literature studies and interviews. The following presents the sub-questions and present a brief resume of the answers found in this report.

- Who are the relevant stakeholders and how do they affect the implementation of PtX in Denmark?

To find the relevant stakeholder, a stakeholder analysis has been conducted. Here it was found that the group called *Regulators* has the highest power in regards to facilitating PTX, mainly being the central administration. The central administration does take a low-risk approach towards PtX, where they mainly help subsidise demonstration projects at the moment. This approach is taken due to uncertainties linked to PtX technology and its political impacts. Even though many politicians are recognising the potential of PtX, there are currently cheaper alternatives that can reach the 70 % emission reduction goal set for 2030. The urgency of developing PtX is therefore impacted by the political reality and will potentially suffer from not being a *No Regrets* solution. However, new lobbyist groups can impact the current political agenda to increase support to PtX technologies in the current institutional-market-system through policy changes.

- What are the socioeconomic benefits of implementing PtX?

The socioeconomic benefits of implementing PtX was found to be highly dependent on regulatory framework, markets and the application of methanol. It was seen through the energy systems analysis that the way of climate benefits of PtX has a high influence on the feasibility of PtX, to the point where it can determine whether it is a good investment or not. Other socioeconomic benefits were also estimated but were not directly compared to financial estimation since these were regarded to be incomparable.

- What are the parameters affecting the socioeconomic feasibility of PtX in a Danish context?

Through a literature study and interviews the different socioeconomic parameters were determined to be as seen in table 4.2. In this study, the main discussed parameter was that of the climate costs, which was tested in the sensitivity analysis.

- What PtX solution is most easily applicable to the Danish society before 2030?

Throughout the literature study on PtX and interviews with relevant stakeholders, where they were asked their opinion in regards to the easiest applicable PtX solution in the current Danish energy system. Here the majority expressed that from their point of view this is methanol, which was chosen to be the candidate for all analyses in this project.

As seen from the sub-questions, the approach towards answering the research question has been aimed at both including the socioeconomic- as well as institutional-considerations. The energy systems analysis provides information on the effects of the socioeconomic elements in the feasibility study of PtX. The stakeholder analysis clarifies the interconnections between the actors that have importance and power in the PtX development. Together these results can outline how a feasible pathway can be developing for PtX in Denmark.

7.2 Methodological Discussion

The various methods used through the study are discussed in this section to determine their effects on the validity of the project and the results gained through this project. Because of this, the emphasis will be put on the methodology and theoretical framework that the project operates within.

7.2.1 Innovative Democracy

The institutions and market economy are approached in this report from an *Innovative democracy approach* which can affect the results. This approach is, therefore, part of the basic understanding from which the stakeholder and the energy system analysis is investigated. This has had a direct influence on the stakeholders included in the stakeholder analysis in chapter 5. As seen in Figure 5.2 on page 62 the stakeholders presented in the group *New Lobbyist with direct economic interest* and the group *Lobbyist without direct economic interest* role would not be considered if one of the other approaches would have been used instead. In the innovative democracy approach, the segregation of stakeholders into different lobbyist groups therefore increases the visibility on how these can participate and influence the democratic process. Since this report concerns a radical technological change which would be conducted by new technologies, it is estimated that without the influence of these new stakeholder groups, the new technology would not be able to penetrate the market. At least not to a point where it can become competitive with technologies already dominating the existing markets.

Some of the assumptions used throughout the energy systems analysis are highly dependent on the success of various New- and Non-economic involved -Lobbyist. An example of this would be the applied socioeconomic value of avoiding CO_2 emissions that was used throughout all scenarios. In the current framework, this revenue would not be given directly to the producers since it is an estimation of the monetary value of avoiding the damage caused by the effects of the emission. To make this revenue a reality for the plant it would require either indirect market policy in the form of a subsidy given to emission avoiding fuels, or through a direct market policy where an added CO_2 tax applied directly for the transport sector, thereby creating incentive by making fossil fuel transportation more expensive.

This would, of course, cause an issue if applying the analysis to an economic system not accounting for the socioeconomic effects, but solely looking into the business case of a system, which emphasises the necessity of ensuring the inclusion and the possibility of reforming political processes if the business economic gains are to match those of the socioeconomic ones. This, therefore, calls for considerations of both socioeconomic and business economic considerations which can be linked together in a feasibility study.

One of the more noticeable effects of recognising and including the new lobbyist group can be observed on the results obtained through the sensitivity analysis conducted in the energy system analysis. Here one of the parameters tested was the influence of using a suggested CO_2 value of 200 €/ton of CO_2 suggested by The climate council. As discussed in chapter 5, *The climate council* can be considered as a *lobbyist without a direct economic interest*, which would not be included if the market economy approach was considered differently. The price of 74 €/ton used in all of the scenarios is considerably lower of the one suggested by *The Climate Council*, which has a huge impact on the NPV obtained as a result. However, this effect was explored in the sensitivity analysis and showed that a positive NPV could be achieved.

Other examples outlining the requirements of the innovative democracy approach are also linked to criteria such as a lowered tariffs and subsidies for investments are to applied to become a reality. It can therefore be seen that this approach have a high influence on what can generally be concluded in this report. This emphasises the general requirements of including all the new lobbyist from the *Innovative democracy approach*, in the determination of direct- and indirect -market policies, for matching the socioeconomic values to the business economic revenues and cost. Furthermore, this enhances the importance of conducting a feasibility study which investigates how feasible a certain solution is to a given problem considering both business and socioeconomic studies to create a new market situation through public regulation.

7.2.2 Feasibility Study

In Chapter 4 the characteristics and appliances of feasibility studies were presented. In this project, it was chosen to conduct a socioeconomic feasibility study in compliance with the research question. Based of the feasibility study design the socioeconomic effects were given a value, and from these values, the alternative system (using methanol for transportation) was compared to the current system (using fossil fuels for transportation). The results obtained through the feasibility study are therefore highly relying on the value given socioeconomic effects of the system, mainly being the price of the CO_2 avoided. From the sensitivity analysis, it was observed that using an estimation of CO_2 cost proposed by the Climate Counsel (The Climate Council 2020) would change the NPV from being negative to providing a profit. While this price for CO_2 was approximately eight times higher than that of the current CO_2 quota price, and more than twice the price of mitigating action used as the basis for the scenarios, this price could very-well be as accurate as the others presented. Different studies have different methodologies of determining the cost of GHG emissions, and therefore different values assigned to this, as shown in this report. When choosing a specific value assigned for the CO_2 emission the aim was to both account for the true value of the emissions and a price that could to some extend be realistically implemented if the system was to be changed through public regulation. The cost of mitigating action was therefore considered the adequate choice. The results should however be observed with this in mind: Socioeconomic cost are highly dependent on the methodology used for estimating this, and the true cost of emissions vary depending on which research you refer to.

As the idea of conducting feasibility studies is to investigate alternatives it can be discussed if this study, which investigates electrification of the transportation sector, also would benefit to compare the production and use of electrofuels to that of electric vehicles (EV's). EV's could prove to be a better solution for electrification of the transportation sector but was dismissed due to the focus of the problem-formulation not being on direct electrification of the transportation sector. Both EV's and electrofuel power vehicles have upsides when comparing them to each other, EV's having higher efficiency and electrofuel enabling a more centralised production. These upsides could be further explored in future studies and this study is encouraged if a national large scale electrification of the transport sector, either directly or through electrofuels is decided. This study does however only focus on the potential of electrofuels, which is why EV's are left out and therefore not been investigated.

7.2.3 Method of Determining Sustainability of Methanol

As presented in Chapter 4 section 4.3.3, the main parameter for determining the sustainability of the methanol production was that used to define biofuels that compare its reduction of GHG emission to those emitted if the biofuels were not used. Here it was presented that for the electrofuel to be considered sustainably produced, the total emissions of use and production had to be less than 127.83 g CO_2/kWh.

Some elements were excluded from the CO_2 emissions such as the emissions associated with equipment production, which could potentially bring the maximum allowed CO_2 emissions further down, and with that further limit the production hours and decrease the profitability of the system. It was however assumed as the yearly profiles approach 2030, the RE of the electricity system increases, therefore increasing the CO_2 emissions avoided when producing. As such it can be assumed that the closer to 2030 a PtX production is started the more sustainable electrofuels can be produced. However, this is only for productions which receive electricity from the main grid without behind the meter RES.

The used sustainability calculation method for the biofuels is not necessarily mandatory for electrofuel. Currently, there are not any requirements as to what reduction the electrofuel have to achieve to be defined as sustainable. In principle, the plant could therefore have been designed to produce at all hours, and not have any requirement for flexibility.

This would mean that production hours could be increased resulting in the investment cost of the hydrogen storage and the electrolyser capacity to decrease, thereby increasing the revenue and decreasing the investment costs. The reason for limiting the production requirements rely on the conviction that new solutions have to be sustainable from an *environmental* aspect as this is part of this reports understanding of sustainability. To achieve environmental sustainability the applied method seem adequate prior to 2030 in the Danish context. The exact time for when the electricity in the entire grid is 100% from RES is different for each nation, which is why this approach provides valuable knowledge on the CO_2 linked to the product. Even after 2030 when all electricity in Denmark will come from RES, the electricity consumed for PtX products is most likely to be dealt with by certificates eg. *guarantees of origin*. Due to the interconnectors and how the electricity market is constructed, the PtX sector still has to consider the CO_2 content in the electricity used after 2030. Ensuring that electricity is sustainable produced comes at a cost which therefore affects the feasibility of the PtX solutions.

7.3 Stakeholder Discussion

In chapter 5 the relevant stakeholders for *Developing PtX in Denmark* are outlined according to the theory presented in the methodology. This analytical approach investigates the entire PtX sector and is not scoped to the specific PtX pathway investigated in the energy system analysis as presented in chapter 6. The analysis of the entire PtX sector provides a broader insight into the current reality is assumed more relevant than only investigating one PtX pathway. The analysis, therefore, views at the more overarching regulator stakeholders than at the specific level due to the uncertainties of the various PtX pathways. This outlines key stakeholders for the entire development of PtX as a sector while an investigation with a more specific scope would only be relevant for the certain PtX pathway. The scope of the stakeholder analysis is chosen since the PtX sector is seen as a novelty sector and therefore benefit from a broader investigation to provide insight to how the entire sector can change. This is especially relevant when the investigation focuses on the socioeconomic benefits for society. Scoping the stakeholder analysis to the power-to-methanol could describe the selected pathway in more detail but could also disregard important insights as to how the development of the entire PtX sector in Denmark is impacted by stakeholder.

It is furthermore difficult to outline the relevant stakeholders for the specific pathway since only three projects of the investigated pathway are observed in the Danish context based on Figure 1.8 on page 13. Of the three projects, only *Power2Met* and *eSMR-MeOH* are pilot or demonstration projects and operating in the period of 2019 to respectively 2021 to 2023. Through the broader scope, the entanglement of the various PtX pathways are furthermore observed since the *Producers* group contain all PtX pathways and therefore also show how changes for one pathway potentially can affect the other PtX pathways. The entanglement is also seen in the outlined example in chapter 5 where different stakeholders involve themselves in the PtX sector as presented in the proposed large scale PtX plant in Copenhagen (Ingeniøren 2020). The entanglement of the PtX industries pathways are also seen in energy system analysis in the valuation of CO_2. This value has a significant impact on the feasibility study which is relevant for various PtX pathways. In the same manner, taxation on CO_2 can impact the industry and consumers using fossil fuels which can push for alternatives which can be created by PtX.

Especially the decisions on the valuation of inputs such as CO_2 and what to include in an economic evaluation is therefore observed to be important since this is used in the central administration (DEA, The ministry of CEU) to investigate PtX in the Danish context and create the decision-making basis for the Danish parliament. If this process is developed from a more neoclassical or concrete institutional approach relevant inputs from stakeholders are therefore potentially excluded or eliminated. The approach towards institutions and markets is therefore not irrelevant for the analysis, but determining the prevailing approach in the Danish context can be difficult. The various stakeholders often have different approaches to this, which naturally affect the stakeholder analysis and potentially also the results of it. To fully comprehend this factor an in-depth analysis of all stakeholders is required where interviews can determine the stakeholders' approach and understanding of markets and institutions. In general, a more detailed investigation of the stakeholders can imaginably change their placement in the outlined overview. Also, other stakeholders could have been included and some could have been excluded which all potentially change the result of the analysis. Changes in how stakeholders such as *Energinet, Evida* and *Electricity DSO's* are regulated, can as discussed in the stakeholder analysis, also change these stakeholders power and importance, which potentially can increase if an agreement based approach is introduced. Furthermore, the stakeholder analysis could be supported and benefit from separate analyses to determine the stakeholders from power theory, discourse theory, theory on decision arenas, participation processes and relationship theory. This would give more insights on how stakeholders are affected by different types of power and relationship in between each other (power and relationship theory) and how the discourse can be used to promote certain beliefs (discourse theory). This can affect the certain solutions being discussed and how they are discussion (decision areas) and how potential new stakeholders are excluded or included into this discussion (participation processes). Doing this will also increase the validity of the stakeholder analysis since the information is observed through a more complex understanding of the stakeholders which can bring the researcher closer to reality.

These are not investigated based on the problem field outlined by the research question which emphasises on both a technological investigation and not strictly the institutional context of how PtX can be implemented.

The stakeholder analysis nonetheless provides an adequate foundation upon which the general understanding of the decision-making process in Denmark. When this knowledge is combined with the understanding of radical technological change from an innovative democracy approach information on how to impact the development of PtX in Denmark becomes clear. Relating this to the energy system analysis can therefore help to understand how the results from this investigation can be impacted to potentially realise the socioeconomic gains outlined.

7.4 Energy Systems Analysis Discussion

The *Energy System Analysis* Chapter's main objective is to assess the socioeconomic benefits of different scenarios and test their sensitivity to different parameters. The results are then interpreted to analyse if it is beneficial from a socioeconomic point of view for the Danish society to invest in power-to-methanol plants in the near future. The conclusion was that with the current regulatory framework and using already a CO_2 price that is 3 times the current quota price, power-to-methanol still had a negative IRR and NPV. The results are naturally very dependent on the assumptions and prices used in the scenarios and it could potentially be feasible if different prices were used. Even though it is likely to be unfeasible, implementing PtX is a solution to reduce GHG emissions and the technology is still in the early stages. Having more applications of the technology can help increase the TRL and therefore reduce the investment costs. For these reasons, it is still assumed that PtX can play an important role in the future energy system and in Section 6.5 a possible pathway to implement PtX in Denmark is presented. The following paragraphs discuss the choices made throughout the analysis and how they affect the results.

7.4.1 Plant Design

As discussed in Section 6.1 on page 67, alkaline was the technology chosen for the electrolyzer due to lower investment prices and suitable efficiency. Alkaline is more established when compared to PEM and SOEC, even though there are potential advantages of using newer technologies. Despite having a lower efficiency than the alkaline, the PEM electrolyzer is the most flexible and can be used to provide ancillary services to the TSO. These services would add extra yearly revenue, but would also add an extra investment cost of the PEM electrolyzer. There are different services and they vary in response time required, duration, capacity and value (Energinet 2020*b*). The main reason why ancillary service was not considered is that it would be hard to manage the hydrogen production and consumption balance if the electrolyzer's operation cannot be predicted. When considering deploying multiple plants throughout the country, it is assumed that if all of them were to offer frequency restoration services, the market would saturate, decreasing the potential revenues.

Power-to-methanol and other types of PtX require a CO_2 source to bind the carbon atoms to the hydrogen and form organic molecules. Biogas plants were chosen as the CO_2 source for all scenarios because the CO_2 stream that comes out of the upgrading unit is very pure in CO_2 and does not have many contaminants.

There is also the possibility of selling heat back to the biogas plants and the plants are usually located in rural areas, meaning that it could facilitate direct connections to wind turbines, as opposed to if it was placed near cities. However, if many power-to-methanol plants are to be deployed, the CO_2 supply from biogas plants might not be enough to cover the demand and other sources would be required. One alternative is wastewater treatment plants, as they can use the oxygen and heat byproducts and can supply CO_2 from the aerobic digesters. Another option is to use the CO_2 from some industrial processes, but it usually requires some purification operations which adds an extra cost. As PtX develops in the future and the cheapest CO_2 sources are taken, it is possible that CO_2 will not be given free of charge anymore as it was assumed in the analysis. Naturally, some PtX applications such as power to hydrogen and power to ammonia are not dependent on a CO_2 source and would not be affected.

7.4.2 Results

The scenario building was done for what would be an average location for building a power-to-methanol plant, rather than a specific location. While it makes it easy to upscale to a national perspective as it was done in Section 6.5, it becomes harder to estimate some inputs due to it not being based on an actual location. For example, it is harder to estimate the distance do district heating networks or if there is any potential oxygen buyer in the proximity. Another uncertain factor is how much wind capacity can be placed and directly connected to the plant. To deal with the uncertainty, a conservative estimation was done. For the *Onsite* scenario, the oxygen sales were set at 0 %, the heat is only sold to the biogas plant and the wind capacity is 2 times the consumption. The conservative approach was chosen because the cost of laying down and operating hot water pipes, the cost of transporting the oxygen and the cost of the cables to connect directly to the wind turbines are not considered in the model. Nonetheless, the results obtained from the scenario analysis were used to measure the difference caused by having a behind-the-meter connection to wind turbines.

It was clear that the feasibility was better when the wind turbines were added. Comparing the *Onsite +* to the *Onsite* shows that even being able to sell all the heat and oxygen and having a lower cost for retrofitting the cars, the NPV is still negative.

Tariffs compose part of the electricity cost in all scenarios, having a higher impact on the *Offsite* scenario. One topic that is often discussed is if and how flexible tariffs can be implemented in Denmark (Tornbjerg 2018). The concept is that the DSO and/or TSO tariffs would change depending on the hour of the day to stimulate a more distributed electricity consumption. This concept becomes increasingly important in a future energy system with a large share of electric vehicles and therefore is getting increased attention. Even though flexible tariffs are not considered in the energy system analysis, it would be possible to adapt the model to consider hourly flexible tariffs and add that to the total electricity price. This is also possible because the electrolyzer is not operating all hours of the day and can avoid running in hours with a high total electricity cost.

Part of the costs of the tariffs can be saved when implementing a behind the meter solution, which also has a higher CO_2 savings. It was clear from the scenarios and the sensitivity analyses that wind power behind the meter significantly increases the feasibility of power-to-methanol. However, when looking at it from a planning perspective there is the issue of placement of these onshore wind turbines next to the power-to-methanol facility. A positive side is that the facilities would be placed next to biogas plants, which are usually located in more rural areas. This still poses a challenge because of factors such as distance to roads and houses, shadowing, noise generation and others. Furthermore, there are already numerous onshore wind turbines in Denmark, which is why the potential to put up additional turbines is considerably lower onshore than offshore. Also, the 2018 Energy Agreement aims to limit the number of wind turbines from 4 300 to 1 850 in 2030 (Regeringen 2018). However, the onshore wind turbines sites can be reused after the lifetime of the existing turbine and therefore potentially avoid a problematic planning process. This would rely on changes in the regulatory framework of how *behind the meter* solutions can be developed unless the wind capacity can be placed within the same cadastre as the plant. This can be achieved by regulatory free-zones where a wind capacity can be considered a *behind the meter* solution despite not being on the same cadastre as the PtX plant. The realisation of the *regulatory free zones* could help facilitate PtX, as this would decrease the costs of transmission and distribution fees and not limit the placement of wind turbines to the same cadastre as the PtX plant. This concept of regulatory free-zone is vaguely mentioned in the energy agreement from 2018 as a possibility to create a smarter and more flexible energy system (Regeringen 2018).

The sensitivity analysis furthermore showed that going from a wind to electrolyzer ratio of 1:1 to a ratio of 2:1 had a large impact on the NPV, but that going from 2:1 to 3:1 had a much smaller impact. Another point of discussion is the optimization vs. simulation. In the analysis, while some parameters were tested and changed to fit a local minimum, it can't be said that the results obtained were fully optimized. Therefore, it can be said that the analysis was mostly composed of simulation and not optimization. (Lund et al. 2017) As a result, the NPV values obtained in the scenarios are most likely not the global minimum and therefore could be further improved with better optimization.

Another consideration that could potentially improve the NPV of the scenarios is the reductions in other types of emissions. While the CO_2 savings obtained when replacing gasoline with sustainable methanol are accounted for in the NPV, the monetary values of reducing NO_x and particulate matter emissions are not accounted for. NO_x causes adverse health effects (Organization 2013) and acts as a precursor of both tropospheric ozone (O_3) and particulate matter (Beelen, R. et al. 2014).

All in all, the *Onsite* and *Onsite +* results show that even using a CO_2 price of 3 times the EU ETS quota price, the NPV of the power-to-methanol plant is still negative. This suggests that in order to be feasible, some inputs need to be changed. The sensitivity analysis conducted in Section 4.3.3 concluded that the most sensitive parameters are the CO_2 price, the gasoline price, the investment, the electricity price and the TSO and DSO tariffs. Out of these, the gasoline and the electricity price are dictated by the market and in that sense very external to the scope of PtX development. The ones that can be influenced in the national context are the CO_2 price, the investment and the tariffs. However, from a socioeconomic point of view, a decrease in tariffs for PtX applications would not increase its feasibility because it is assumed that the tariffs for the other customers would increase as a reaction. As a result, the cost for society would remain the same. The investment cost should decrease as more PtX applications are implemented and the TRL increases. The most uncertain parameter and to a certain extent easiest to control is the CO_2 price. In the analysis, the CO_2 mitigation price of 74 €/ton is used, but some reports suggest that a higher price should be used. The CO_2 price determined by the government will have a great impact on the feasibility of power-to-methanol applications and could potentially be one way of implementing a PtX subsidy that is based on the amount of CO_2 saved. The subsidy could be applied through a tender scheme for sustainable electrofuels. The main advantage of doing a tender scheme is that the government has more control over how much subsidy is given, but at the same time would have more reach than a demonstration progress funding.

Conclusion 8

This report investigated pathways of applying the socioeconomic potential of a power-to-methanol solution in to Danish the transportation sector. This was done based on the understanding that PtX can provide a sustainable alternative to fossil fuels in the transportation sector and therefore help to achieve the political goals set for 2030. This has been investigated through the research question:

How can the potential socioeconomic effects of implementing Power-to-x for transportation before 2030 in Denmark, be applied?

The research question was answered through the methodological approach from the research design as presented in Figure 4.1. The stakeholder analysis was conducted to outline how various stakeholders can affect the development of PtX in Denmark. This was investigated through the innovative democracy approach where the necessity of establishing and empowering new institutions in the market is emphasised to achieve a radical technological change in the existing system. The stakeholder analysis showed that PtX development is highly affected by the central administration and the decisions made in the Danish parliament. The central administration and especially the DEA, who ensures the Danish energy supply, directly facilitates demonstration project support through EUDP but are still depending on the industry to take the lead on large scale implementation of the technology. This position is taken because they are caught in the middle of the industry push for it and the political framework which mainly is concerned about reaching the emission reduction targets of 2030 at the lowest cost. Since PtX is an expensive and less efficient solution than other alternatives, the incentive for implementing PtX is lacking when looking at the near future. This incentive can be created in the system through added policies which either directly or indirectly affect the existing market or institutional market design. This can potentially change the feasibility of PtX project in the Danish context based on the political will which can be strengthened and showcase where changes in the framework are to happen by including the *new lobbyists with economic interest* even further. The result of the stakeholder analysis, therefore, shows who can create change and how changes can be introduced in the system if PtX has to become feasible in the near future and be part of the Danish energy system before 2030.

The Energy systems analysis presented various options for producing and using methanol from power. From this analysis, it was seen that to fulfil the production criteria set up in the methodology the *Onsite* and *Onsite +* had an improved socioeconomic feasibility than the other scenarios. Both of these scenarios produced methanol to be used in retrofitted fuel cell cars and sourced electricity from wind turbines in a behind-the-meter solution.

None of the tested scenarios were found to have a positive NPV, which could indicate that the technology is not feasible at the current stage. The *Onsite* scenario which was used for sensitivity parameter testing had an NPV of -19.8 million €. From the sensitivity analysis it was however found that changing the value of GHG emissions avoided from that used by (Carbon Pricing Leadership Coalition 2017) to the one used by the climate council (Klimarådet 2020*b*), could change the feasibility of the plant, and create an NPV of approximately 12.6 million €. Since this is a socioeconomic cost the accurate value of avoiding climate damage is hard to be estimated. The same goes for other societal benefits such as the domestic turnover and job-creation effects of implementing PtX. For one plant, the domestic turnover was estimated to be approximately 42.7 million € and the job creation was estimated to account for 29 jobs for 22 years. However, these values are not included in the NPV calculations. Lastly, it was observed that the Danish biogas sources could provide CO_2 sources for a capacity corresponding to that of 40 plants nationwide, which could lead to GHG emission savings corresponding to 4.8% of the entire transportation sector.

Even though the analysis concluded that power-to-methanol was found to not be socioeconomic feasible in the current regulatory framework, a pathway to implementing it in Denmark has been outlined. The main driver is to reduce the GHG emissions from the transport sector to achieve the 2030 emission goals. In addition, the more PtX applications there are, the quicker the TRL will increase and investment cost decrease. According to the innovative democracy system, the policies and regulations around PtX need to change through reforming political processes. The sensitivity analysis showed that the CO_2 price is a strong lever to increase the feasibility of PtX and is something that could be determined by the *Regulators* stakeholder group. Determining a suitable value of avoiding GHG emissions would be the first step of possible large-scale PtX implementation. Using this value, it can be properly determined whether the presented PtX solution can be considered feasible or if it should be disregarded in favour of other emission-reducing solutions for the transportation sector. If the PtX solution is then found to be feasible, the second step would be including a subsidy to match the value of avoiding GHG emissions. The subsidy could be incorporated into a tender scheme aimed at promoting a sustainable transition in the transportation sector. This can be created through the democratic process where the *new lobbyists with economic interest* need to push for a different valuation of CO_2 which can impact the central administrations' calculations methods and therefore the feasibility of PtX in the Danish context.

9 Future Research

The results and conclusions outlined throughout this report could be further developed if additional research and analysis were conducted. Some of these are described below:

- The analysis could be scoped to one or a selection of the 21 possible biogas plants outlined in Section 6.6. It would enable more accurate values for district heating connection potentials, oxygen sales, wind turbines potential and DSO tariffs. This could be achieved by mapping the most adequate placement of PtX plants based on.
- The feasibility of PtX could be compared to the feasibility of large-scale implementation of EV's. This comparison would indicate which partway would be the most suitable when transforming the transportation sector from using fossil fuels to using renewable energy.
- In this report, only the feasibility of power-to-methanol was investigated. Applying the same feasibility study methodology to other PtX products such as hydrogen, ammonia and jet fuel would provide a good comparison between the technologies.
- Investigating the market development and potential for methanol fuel cell cars could furthermore provide insights on how plausible a future based on new methanol fuel cell is compared to retrofitting cars.
- Further research into the technology found in the *teknologi katalog* (Danish Energy Agency 2017) would also enable more accurate investigations of the PtX sector in the Danish context. A good example of this is the investment cost of the methanol plant which is estimated to covers a capacity span between 3 and 33 MW. Naturally, a higher capacity would enable a reduction in the investment price. A proper investigation on investment reduction with capacity increase and future technological development could therefore yield results with an increased NPV.
- Understanding the development of the Energy sector in Denmark in a more comprehensive manner and how different choices are outlined and selected in the central administration would furthermore enable a deeper insight to how PtX is positioned in the Danish context.

Investigating these future work suggestions could potentially change the feasibility of implementing PtX in the near future and hereby create other pathways for its implementation in the Danish Energy System.

Bibliography

Auken, I. (2020), 'Interview on the 9th of march 2020, copenhagen'.

Beelen, R. et al. (2014), *Effects of long-term exposure to air pollution on natural-cause mortality: an analysis of 22 European cohorts within the multicentre ESCAPE project*, Avaliable at: [Website]. (accessed on 25th of May 2020).

Brintbranchen (2018), *HyLAW National Policy Paper - Denmark*, Available at: [Website]. (accessed on 14th of February 2020).

Brown, R. B. (2006), *Doing Your Dissertation in Business and Management*, Avaliable at: [Website]. (accessed on 7th of April 2020).

Carbon Pricing Leadership Coalition (2017), *Report of the High-level Commission on Carbon Prices*, Avaliable at: [Website]. (accessed on 21th of March 2020).

CertifHy (2020), *Why a Guarantee of Origin for Green Hydrogen?*, Avaliable at: [Website]. (accessed on 26th of March 2020).

Chehade, Z., Mansilla, C., Lucchese, P., Hilliard, S. & Proost, J. (2019), *Review and analysis of demonstration projects on power-to-X pathways in the world*, Avaliable at: [Website]. (accessed on 16th of February 2020).

Chevalier, J. (2001), *Stakeholder Analysis and Natural Resource Management*, Avaliable at: [Website]. (accessed on 28th of March 2020).

Danish Energy Agency (2014), *Energiscenarier frem mod 2020, 2035 og 2050*, Avaliable at: [Website]. (accessed on 5th of March 2020).

Danish Energy Agency (2017), *Technology Data for renewable fuels*, Avaliable at: [Website]. (accessed on 21th of March 2020).

Danish Energy Agency (2018*a*), *Energistatistik 2018*, Avaliable at: [Website]. (accessed on 3th of March 2020).

Danish Energy Agency (2018*b*), *Technology Data Energy Storage*, Avaliable at: [Website]. (accessed on 5th of May 2020).

Danish Energy Agency (2019*a*), *Basisfremskrivning 2019*, Avaliable at: . (accessed on 5th of March 2020).

Danish Energy Agency (2019*b*), *Energistyrelsen støtter Power-to-X projekter med 128 mio. kr.*, Available at: [Website]. (accessed on 19th of February 2020).

Danish Energy Agency (2019*c*), *Samfundsøkonomiske beregningsforudsætninger for energipriser og emissioner*, Avaliable at: [Website]. (accessed on 27th of April 2020).

Danish Energy Agency (2020*a*), *Alternativ Drivmiddelmodellen*, Avaliable at: [Website]. (accessed on 27th of April 2020).

Danish Energy Agency (2020*b*), *Energy Statistics 2018*, Avaliable at: [Website]. (accessed on 1th of March 2020).

Danish Energy Agency (2020*c*), *Om energistyrelsen*, Avaliable at: [Website]. (accessed on 27th of April 2020).

Danish Energy Agency (2020*d*), *Teknologikataloger*, Avaliable at: [Website]. (accessed on 27th of April 2020).

Danish Ministry of Climate, Energy and Utilities (2019), *Denmark's Integrated National Energy and Climate Plan*, Available at: [Website]. (accessed on 15th of February 2020).

Dansk Energi (2019), *Elforsyningensnettariffer og priser Pr. 1. januar 2019*, Avaliable at: [Website]. (accessed on 31th of May 2020).

Decourt, B. (2019), *Weaknesses and drivers for power-to-X diffusion in Europe. Insights from technological innovation system analysis*, Avaliable at: [Website]. (accessed on 17th of February 2020).

Egestrand, M. (2020), 'Interview on the 16th of march 2020, online'.

EMD International (2014), *User's Guide EnergyPRO*, Avaliable at: [Website]. (accessed on 8th of May 2020).

Energi, D. (2020), *Elforsyningens nettariffer og priser*, Avaliable at: [Website]. (accessed on 27th of May 2020).

Energinet (2018), *Systemperspektiv 2035*, Available at: [Website]. (accessed on 18th of February 2020).

Energinet (2019), *PTX I Danmark Før 2030*, Avaliable at: [Website]. (accessed on 11th of February 2020).

Energinet (2020*a*), *Declaration, Emission per Hour Data*, Avaliable at: [Website]. (accessed on 27th of April 2020).

Energinet (2020*b*), *Hvad er systemydelser?*, Avaliable at: [Website]. (accessed on 8th of May 2020).

Energinet (2020*c*), *Om Os*, Avaliable at: [Website]. (accessed on 27th of April 2020).

Energinet (2020*d*), *Systemperspektiver ved 70 %-målet og storskala havvind*, Avaliable at: [Website]. (accessed on 20th of March 2020).

Energinet (2020*e*), *Tariffer og Gebryer*, Avaliable at: [Website]. (accessed on 27th of April 2020).

Energinet (2020*f*), *Økonomi*, Avaliable at: [Website]. (accessed on 25th of March 2020).

European Commission (2010), *Energy 2020: A strategy for competitive, sustainable and secure energy*, Avaliable at: [Website]. (accessed on 13th of February 2020).

European Commission (2011), *Clean energy for all Europeans*, Avaliable at: [Website]. (accessed on 13^{th} of February 2020).

European Commission (2014*a*), *2030 climate & energy framework. Climate Action*, Avaliable at: [Website]. (accessed on 13^{th} of February 2020).

European Commission (2014*b*), *A policy framework for climate and energy in the period from 2020 to 2030*, Avaliable at: [Website]. (accessed on 13^{th} of February 2020).

European Commission (2015), *Energy Union Package: A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy*, Available at: [Website]. (accessed on 13^{th} of February 2020).

European Commission (2018), *A Clean Planet for all: A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*, Available at: [Website]. (accessed on 13^{th} of February 2020).

European Commission (2019*a*), *Annex to the Communication on the European Green Deal. Roadmap - Key actions*, Available at: [Website]. (accessed on 14^{th} of February 2020).

European Commission (2019*b*), *The European Green Deal*, Available at: [Website]. (accessed on 15^{th} of February 2020).

European Commission (2019*c*), *Fourth report on the State of the Energy Union*, Available at: [Website]. (accessed on 13^{th} of February 2020).

European Environment Agency (2017), *Range of life-cycle CO2 emissions for different vehicle and fuel types*, Avaliable at: [Website]. (accessed on 21^{th} of March 2020).

European Union (2018), *Directive (EU) 2018/2001 of the European Parliament and of The Council of 11 December 2018 on the promotion of the use of energy from renewable sources*, Available at: [Website]. (accessed on 13^{th} of February 2020).

European Union (2020), *Hydrogen*, Avaliable at: [Website]. (accessed on 1^{th} of March 2020).

Eurostat (2020*a*), *Greenhouse Gas Emissions*, Available at: [Website]. (accessed on 15^{th} of February 2020).

Eurostat (2020*b*), *Primary Energy Consumption*, Available at: [Website]. (accessed on 17^{th} of February 2020).

Eurostat (2020*c*), *Share of renewable energy in gross final energy consumption*, Available at: [Website]. (accessed on 15^{th} of February 2020).

Eurostat (2020*d*), *SHARES*, Available at: [Website]. (accessed on 15^{th} of February 2020).

Evida (2020*a*), *Hvad laver Evida*, Avaliable at: [Website]. (accessed on 27^{th} of April 2020).

Evida (2020*b*), *Økonomisk regulering*, Avaliable at: [Website]. (accessed on 25^{th} of April 2020).

Fuel Cells and Hydrogen Joint Undertaking (2020), *Who we are*, Avaliable at: [Website]. (accessed on 5^{th} of March 2020).

Graves, C. (2010), *Recycling CO2 into Sustainable Hydrocarbon Fuels: Electrolysis of CO2 and H2O*, Avaliable at: [Website]. (accessed on 22^{th} of April 2020).

Greene, J. C., Caracelli, V. J. & Graham, W. F. (1989), *Toward a Conceptual Framework for Mixed-Method Evaluation Designs*, Avaliable at: [Website]. (accessed on 5^{th} of May 2020).

Grøn Energi (2018), *The Competitiveness of district heating compared to individual heating*, Avaliable at: [Website]. (accessed on 22^{th} of April 2020).

Hvelplund, F. (2001), *Electricity Reforms, Democracy and Technological Change*, Institute for Development and Planning, Aalborg University.

Hvelplund, F. (2005), *Erkendelse og Forandring*, Institut for Samfundsudvikling og Planlægning, Aalborg.

Hvelplund, F. (2013), *Innovative Democracy, Political Economy, and the Transition to Renewable Energy: A full-Scale Experiment in Denmark 1976-2013*, Avaliable at: [Website]. (accessed on 25^{th} of April 2020).

Hvelplund, F. (2018), *Innovative Democracy and Renewable Energy Strategies: A Full-Scale Experiment in Denmark 1976–2010*, Avaliable at: [Website]. (accessed on 27^{th} of April 2020).

Hvelplund, F. & Lund, H. (1998), *Feasibility Studies and Public Regulation in a Market Economy*, Institut for Samfundsudvikling og Planlægning, Aalborg.

Hvelplund, F., Lund, H. & Sukkumnoed, D. (2007), *Chapter: Feasibility Studies and Technological Innovation.* In: L. Kørnov, M. Thrane, A. Remmen, H. Lund, ed. *Tools for Sustainable Development,* 1 edn. The Authors and Aalborg Universitetsforlag.

Hvelpund, F. (2015), *Chapter: Innovativ projektevaluering*, Aarhus Universitetsforlag, pp. 99–125. In: F. Arler, M. Mosgaard, H. Riisgaard, ed. *Bæredygtighed - Værdier, Regler og Metoder*, 1 edn.

Hvelpund, F. & Arler, F. (2015), *Chapter: Demokrati og bæredygtighed. Energiområdet som case*, Aarhus Universitetsforlag, pp. 99–125. In: F. Arler, M. Mosgaard, H. Riisgaard, ed. *Bæredygtighed - Værdier, Regler og Metoder*, 1 edn.

Hydrogen Europe (2020), *About Us*, Avaliable at: [Website]. (accessed on 1^{th} of March 2020).

Ingeniøren (2020), *Kæmpeanlæg i Storkøbenhavn skal producere 250.000 ton flydende bæredygtige brændstoffer*, Avaliable at: [Website]. (accessed on 31^{th} of May 2020).

ISCC (2016), *Green House Gas Emissions*, Avaliable at: [Website]. (accessed on 23^{th} of March 2020).

Jensen, M. F. (2020), 'Interview on the 5^{th} of may 2020, online'.

Jørgensen, D. (2019), *Brev fra Klima-, energi- og forsyningsminister til Klima-, Energi- og Forsyningsudvalget*, Avaliable at: [Website]. (accessed on 25^{th} of February 2020).

Kennedy, B. L. (2012), *Chapter: Deduction, Induction, and Abduction*, Avaliable at: [Website]. In: U. Flick ed. *The SAGE Handbook of Qualitative Data Collection.*

Klimarådet (2019), *Status for Danmarksbklimamålsætninger og -forpligtelser 2019*, Available at: [Website]. (accessed on 12^{th} of February 2020).

Klimarådet (2020*a*), *Kendte veje og nye spor til 70 procents reduktion*, Avaliable at: [Website]. (accessed on 3^{th} of March 2020).

Klimarådet (2020*b*), *Kendte veje og nye spor til 70 procents reduktion*, Avaliable at: [Website]. (accessed on 20^{th} of February 2020).

Kvale, S. (2007), *Doing Interviews*, Avaliable at: [Website]. (accessed on 27^{th} of February 2020).

Kvale, S. & Brinkmann, S. (2009), *Interview*, number ISBN: 978-87-412-5198-1 *in* 'Handbook', Hans Reitzels Forlag.

Kørnov, L. (2007), *Chapter: Public Participation.* In: L. Kørnov, M. Thrane, A. Remmen, H. Lund, ed. *Tools for Sustainable Development,* 1 edn. The Authors and Aalborg Universitetsforlag.

Lardon, L., Thorberg, D. & Krosgaard, L. (2018), *Deliverable 3.2 - Full-scale technico-economical assessment of Power-to-gas concept applied to WWTP*, Avaliable at: [Website]. (accessed on 27^{th} of April 2020).

Lund, H. (2014), *Renewable Energy Systems*, number ISBN: 978-0-12-410423-5 *in* '1', Academic Press.

Lund, H., Arler, F., Østergaard, P. A., Hvelplund, F., Connolly, D., Mathisen, B. V. & Karnøe, P. (2017), *Simulation versus Optimisation: Theoretical Positions in Energy System Modelling*, Avaliable at: [Website]. (accessed on 29^{th} of May 2020).

Mathiesen et al. (2015), *IDA Energyvision 2050*, Avaliable at: [Website]. (accessed on 4^{th} of March 2020).

Mendonça, M., Lacey, S. & Hvelplund, F. (2009), *Stability, participation and transparency in renewable energy policy: Lessons from Denmark and the United States*, Avaliable at: [Website]. (accessed on 15^{th} of March 2020).

Methanol Institute (2016), *Methanol Blending Technical Product Bulletin*, Avaliable at: [Website]. (accessed on 21^{th} of March 2020).

Methanol Institute (2020), *Methanol Price*, Avaliable at: [Website]. (accessed on 8^{th} of May 2020).

Ministry of Climate-, Energy and Utilities (2020), *Strategi og styring*, Avaliable at: [Website]. (accessed on 21^{th} of March 2020).

Ministry of Finance (2018), *Den samfundsøkonomiske diskonteringsrente*, Avaliable at: [Website]. (accessed on 25^{th} of March 2020).

Müller, J., Remmen, A. & Christensen, P. (1986), *Samfundets teknologi: teknologiens samfund*, number ISBN: 87-7351-491-8 *in* '2. edition', Systime.

Nagamoto, H. (2001), *Fuel Cells: Electrochemical Reactions*, Avaliable at: [Website]. K.H. Jürgen Buschow and Robert W. Cahn and Merton C. Flemings and Bernhard Ilschner and Edward J. Kramer and Subhash Mahajan and Patrick Veyssière, ed. In: *Encyclopedia of Materials: Science and Technology, 1 edn.*

Neumann, J. V. (1961), *John Von Neumann Collected Works.* A.H. Taub, ed. Pergamon Press.

Nielsen, S. & Skov, I. R. (2019), *Investment screening model for spatial deployment of power-to-gas plants on a national scale – A Danish case*, Avaliable at: [Website]. (accessed on 25^{th} of April 2020).

Nielsen, Steffen; Moreno, D. S. I. R. (2020), *Mapping of biogas methanation potential in Denmark - Based on existing biogas sources*, Avaliable at: [Website]. (accessed on 22^{th} of April 2020).

Nikolaidis, P. & Poullikkas, A. (2017), *A comparative overview of hydrogen production processes*, Avaliable at: [Website]. (accessed on 22^{th} of March 2020).

Niras, BDO & Economic, C. (2018), *Samproduktion dokumentationsrapport*, On behalf of Energistyrelsen and Energitilsynet, Avaliable at: [Website]. (accessed on 18^{th} of March 2020).

Nord Pool (2018), *Historical Market Data*, Avaliable at: [Website]. (accessed on 25^{th} of April 2020).

Organization, W. H. (2013), *Review of evidence on health aspects of air pollution – REVIHAAP*, Avaliable at: [Website]. (accessed on 25^{th} of April 2020).

Overseas Development Administration (1995), *Guidance note on how to do stakeholder analysis of aid projects and programmes*, Avaliable at: [Website]. (accessed on 27^{th} of March 2020).

Peschko, J. (2020), 'Interview on the 14^{th} of may 2020, online'.

Philanderer, G. & Golson, J. (2012), *Encyclopedia of Global Warming and Climate Change; chapter No Regrets options*, Avaliable at: [Website]. (accessed on 17^{th} of May 2020).

Pizzol, M. (2017), *Participatory Scenario Development Facilitator guide.* Material presented in the course "Environment assessments and scenarios" at the B.Sc; Urban-, Energy- and Environmental Planning, 4^{th} semester.

Regeringen (2011), *Energistrategi 2050 - Fra kul, olie og gas til grøn energi*, Available at: [Website]. (accessed on 13^{th} of February 2020).

Regeringen (2016), *Forsyning for fremtiden*, Avaliable at: [Website]. (accessed on 25^{th} of April 2020).

Regeringen (2018), *Energiaftale af 29. juni 2018*, Available at: [Website]. (accessed on 15^{th} of February 2020).

Regeringen (2019), *Aftale om klimalov af 6 december 2019*, Available at: [Website]. (accessed on 13^{th} of February 2020).

Ridjan, I. (2015), Integrated electrofuels and renewable energy systems, PhD thesis, Aalborg University, Avaliable at: [Website]. (accessed on 1^{th} of March 2020).

Sargent, R. G. (2013), *An introductory tutorial on verification and validation of simulation models*, Available at: [Website]. (accessed on 13^{th} of Maj 2020).

Shorten, A. & Smith, J. (2017), *Mixed methods research: expanding the evidence base*, Avaliable at: [Website]. (accessed on 5^{th} of May 2020).

Skatteministeriet (2017), *Elafgiftsloven. Bekendtgørelse af lov om afgift af elektricitet (LBK nr 308 af 24/03/2017)*, Avaliable at: [Website]. (accessed on 25^{th} of April 2020).

State of Green (2019), *Installation begins on Denmark's first zero-subsidy wind farm*, Avaliable at: [Website]. (accessed on 1^{th} of March 2020).

Sustainable Energy Planning Department, AAU (2020), *Energy Maps; Biogas Methanation Sources*, Avaliable at: [Website]. (accessed on 25^{th} of May 2020).

The Climate Council (2020), *Om Klimarådet*, Avaliable at: [Website]. (accessed on 27^{th} of April 2020).

The Danish Agricultural Agency (2020), *Landbrugets drivhusgasudledninger*, Avaliable at: [Website]. (accessed on 22^{th} of April 2020).

The Danish Energy Agency (2019), *Energistyrelsen støtter Power-to-X projekter med 128 mio. kr.*, Avaliable at: [Website]. (accessed on 27^{th} of April 2020).

The Ministry of Climate, Energy and Utility (2019), *128 mio. kr. til udvikling af grønne brændstoffer*, Avaliable at: [Website]. (accessed on 27^{th} of April 2020).

The Ministry of Finance (2017), *Vejledning i samfundsøkonomiske konsekvensvurderinger*, Avaliable at: [Website]. (accessed on 27^{th} of April 2020).

Tian, W. (2013), *A review of sensitivity analysis methods in building energy analysis*, Avaliable at: [Website].

Tornbjerg, J. (2018), *Fleksible tariffer belønner gode vaner*, Avaliable at: [Website]. (accessed on 25^{th} of April 2020).

Trading economics (2020), *Gasoline*, Avaliable at: [Website]. (accessed on 31^{th} of May 2020).

United Nations (1987), *Report of the World Commission on Environment and Development: Our Common Future*, Available at: [Website]. (accessed on 13^{th} of February 2020).

United Nations (1992*a*), *Agenda 21*, Available at: [Website]. (accessed on $13^{th}$of February 2020).

United Nations (1992*b*), *United Nations Framework Convention On Climate Change*, Available at: [Website]. (accessed on 14^{th} of February 2020).

United Nations (1998), *Kyoto protocol to the United Nations framework convention on Climate Change*, Available at: [Website]. (accessed on 13^{th} of February 2020).

United Nations (2015*a*), *Paris Agreement*, Available at: [Website]. (accessed on 13^{th} of February 2020).

United Nations (2015*b*), *Transforming our world: the 2030 Agenda for Sustainable Development*, Available at: [Website]. (accessed on 14^{th} of February 2020).

Vandewalle, J., Bruninx, K. & D'haeseleer, W. (2015), *Effects of large-scale power to gas conversion on the power, gas and carbon sectors and their interactions*, Avaliable at: [Website]. (accessed on 27^{th} of April 2020).

Wagner, R. E. (2002), *Some Institutional Problematics of Excess Burden Analytics*, Avaliable at: [Website].

Weintraub, E. R. (2013), *Neoclassical Economics*, Avaliable at: [Website]. (accessed on 1^{th} of March 2020).

Winther, K. (2019), *Methanol as Moter Fuel*, Avaliable at: [Website]. (accessed on 21^{th} of March 2020).

Zeuthen, J. (2020), 'Interview on the 2^{th} of april 2020, online'.

Scenario Values A

The values used for the various scenarios will be presented in this appendix. The scenarios are all built from the same model, why they share a lot of common values. These values are presented in table A.1.

Element	**Values**
Technical information	-
Capacity of electrolyser	10 MW
Capacity of methanol reactor	0.46 MW
Capacity of hydrogen compressor	0.76 MW
Planned outtage of plant (Annual)	3 weeks
Finacial information	-
Investment (constant)	26 136 850 €
- Electrolyser	6 000 000 €
- Methanol reactor	20 136 850 €
Fixed O&M (yearly values)	605 409 €
- Electrolyser	305 409 €
- Methanol reactor	300 000 €
Varaible O&M (yearly values)	228 889 €

Table A.1: Values used in all scenarios for the energy system analysis. Note that the Investment and the Fixed O&M are the sum of the electrolyser and methanol reactor costs, presented below.

The various scenarios were fitted to achieve the lowest investment cost while also achieving the lowered GHG emissions created as a consequence of the methanol production. Due to this, different values were used for some of the components in the different scenarios. Table A.2 presents these different values for the different scenarios.

Element	*Offsite*	*Onsite*	*Onsite+*	*M15*
Hydrogen storage data	-	-	-	-
- Storage capacity (MWh)	885	84	84	718
- Storage costs	24 398 700 €	2 755 500 €	2 755 500 €	19 889 700 €
Allowed CO_2 limit (g/kWh)	234	600	600	191
Investment to engine change	22 131 000 €	22 131 000 €	14 754 000 €	0 €

Table A.2: Variable values used for the different scenarios.

The production is as discussed in chapter 4.1, dependent on the CO_2 content of the electricity. For the first year of production, the CO_2 profile of the electricity is assumed to be that of 2019 in Denmark. This value of the CO_2 limit is however gradually increased towards 2030, where the CO_2 content of the electricity is assumed to be zero, to simulate the gradual green transition of the electricity grid, required in accordance with the goals of the Danish Parliament. Since the construction of the plant requires two years, this CO_2 limit starts from 2022, where the CO_2 decrease of the grid is already assumed to have commenced. In the model, this means that the CO_2 limit is increased each year. This average increase from 2022 to 2030 in the percentage content of the usable electricity is seen in table A.3. Even though in this report it is assumed that there is no CO_2 in the electricity from the grid after 2030, the Danish Energy Agency suggests that there will be 12 g / kWh of CO_2 for the same period (Danish Energy Agency 2019*c*). However, the impact of adding this to the model would be very small, especially when part of the electricity is supplied by wind turbines.

Year	*Offsite*	*Onsite*
2022	71.3%	78.8%
2023	74.9%	81.5%
2024	78.5%	84.1%
2025	82.0%	86.8%
2026	85.6%	89.4%
2027	89.2%	92.1%
2028	92.8%	94.7%
2029	96.4%	97.4%
2030	100%	100%

Table A.3: Percentage increase of usable electricity in the period from 2022 to 2030. Only *Onsite* and *Offsite* are presented since, the other two scenarios follow the same pattern as the *Onsite* scenario.

Lastly table A.4 presents the different output of the various scenarios. Some of these are also shown in chapter 6.

	Offsite	*Onsite*	*Onsite +*	*M15*
Running hours	6295	6295	6295	6290
Methanol produced	36 513 MWh	36 513 MWh	36 513 MWh	36 484 MWh
Heat production (hourly)	2.81 MWh	2.81 MWh	2.81 MWh	2.81 MWh
Yearly heat production (MWh)	17 557	17 855	17 855	17 621
Heat revenue	226 237 €	230 083 €	460 167 €	227 059 €
Oxygen production (kg / h)	747	747	747	747
Yearly oxygen production	6543.7 ton	6543.7 ton	6543.7 ton	6543.7 ton
Oxygen revenue	0	0	470 611 €	0
CO_2 saved	11 984 ton	14 492 ton	14 492 ton	6031 ton
CO_2 revenue	886 808 €	1 072 437 €	1 072 437 €	446 264 €
Gasoline replaced	8 215 477 L	8 215 477 L	8 215 477 L	4 104 466 L
Gasoline replacement revenue	5 105 726 €	5 105 726 €	5 105 726 €	2 550 829 €

Table A.4: Percentage increase of usable electricity in the period from 2022 to 2030. Only *Onsite* and *Offsite* are presented since, the other two scenarios follow the same pattern as the *Onsite* scenario.

Potential of Excess Heat Sales B

This appendix contains the different distances of the Biogas CO_2 sources considered for the PtX plant in this project. Using *Energy Maps*(Sustainable Energy Planning Department, AAU 2020), the various CO_2 sources with as fitting capacity were estimated. These are presented in Figure B.1.

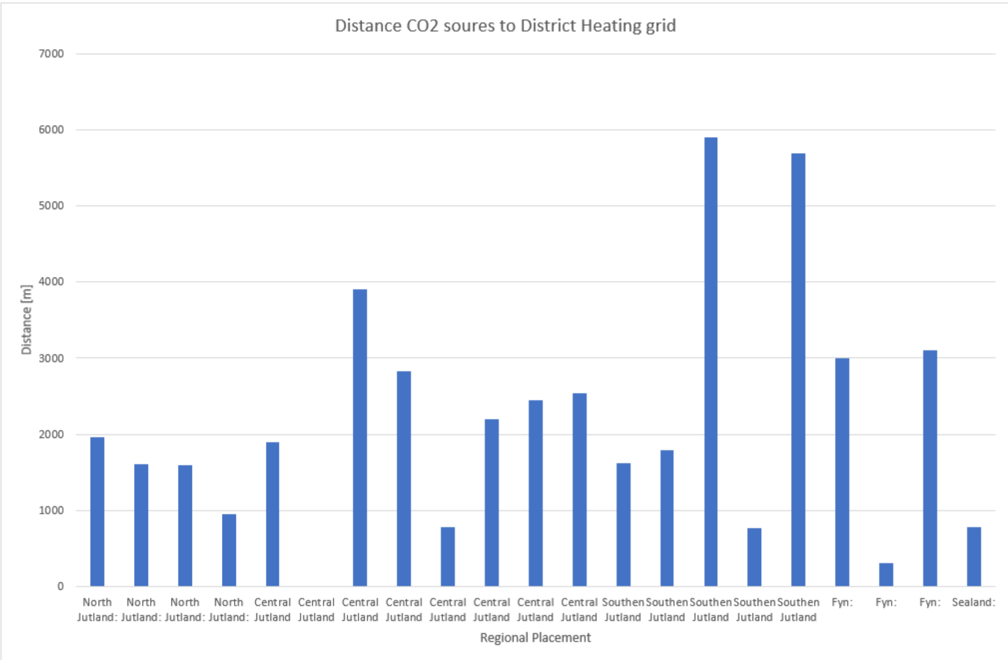


Figure B.1: Distance in meters between the CO_2 source placement and the nearest possible District heating connection.(Sustainable Energy Planning Department, AAU 2020)

As seen in Figure B.1 the distances between CO_2 sources and the district heating vary from 0 m to almost 6000 m. (Grøn Energi 2018) estimating the cost of district heating pipes, accounting for size and geographical placement, as seen in Figure B.2.

Pipe dimension	Green field	Park areas	Outer city	Inner city
DN25	170	216	264	293
DN32	178	224	271	301
DN40	178	224	271	301
DN50	193	239	285	316
DN65	208	255	299	332
DN80	224	270	320	355
DN100	247	301	361	401
DN125	293	347	403	448
DN150	347	409	458	509
DN200	432	502	570	633

Figure B.2: Cost of various district heating pipe cost, accounting for size and area in which they have to placed. Cost in DKK pr. meter. (Grøn Energi 2018)

Using the values presented in Figure B.2, it can be concluded that the cost of the building the required infrastructure for selling the excess heat to a district heating system would not only depend on the distance to the district heating but also the geographical placement and the amount of excess heat produced pr. hour.

Assuming that a DN65 pipe has adequate measurements for getting rid of the heat and that the terrain allows for the lines to be built directly, the cost of building the connection to the district heating could vary from a marginal low cost nearing 0 to that of approximately 2 million DKK.

In the sensitivity analysis, it was seen that heat sales were the lowest influence on the NPV. Due to this and the large span between the infrastructural investment to get rid of the heat, and since this report aims to give a broad estimation of PtX potentials in DK, it was decided not to calculate the exact heating investment cost for each of the plants, but simply assuming that half the heat can be sold off to the biogas plants at the prices presented in the reports.

Interview Guides C

The interview guide serves as the overall structure for the interviews conducted throughout as part of this report. The *Briefing* presented in table C.1 was conducted prior to the interviews where the specific questions as presented in tables C.2, C.3 C.4, C.5 C.6, C.7 and C.8 was asked.

Briefing		
Presentation of the interviewer and the purpose of the interview	Who are we?	We are master student from SEPM at AAU and are writing our master thesis about PtX in Denmark before 2030 and how this will affect the danish society. The group conist of Aksel, Bruno and Tore
	Purpose of the interview	The purpose of the interview is to outline how [interviewees organisation] works with in the danish context before 2030
	Timeframe	There is allocated [X min] for the interview.
	Recording/citing	We are recording the interview to use it in our report. If statements made by you are used these will have to be approved by you afterwards.
	Interviewer	[X] is conducting the interview while the rest of the group take notes.
	Before we begin	If there is anything which is not clear, or you are in doubt about during the interview, do not hesitate to ask. You are always able to withdraw statements, refuse to answer a question or end the interview if you do not want to continue.
Presentation of the interviewee	Personal presentation	Who are you? - Name, age - Education - Previous jobs - Current position (tasks)

Table C.1: General briefing prior to interviews

Ida Auken	Monday the 9^{th} of March 2020. **15 min. face-to-face interview**
Research Question	Question
How and when will PtX be utilised in Denmark?	How do you see the future of PtX in Denmark? Where should it be used? What Is the timeline for this? What are the barriers for PtX in Denmark? What do you see as the biggest framework barrier for PtX in Denmark? What is being planned to overcome it?
How does the government support PtX?	How do you see the support towards PtX developing? Do you see a subsidy being considered? And how should this be structured?
How can the socioeconomic parameters affect the government's view on PtX?	Do you see PtX as the new wind fairytale for Denmark? In terms of socio economics, exporting the technology and being the vanguard of the sustainable transition

Table C.2: Interview question for Ida Auken from Radikale Venstre. Interview conducted in Danish.

Jacob H. Zeuthen	Thursday the 2^{th} of April 2020. **15 min. phone interview and mail correspondence**
Research Question	Question
How is PtX investigated	What is the most easily applicable PtX solution to substitute fossil fuels in the transportation sector? Do PtX products play a significant role in the transportation sector in regards to the 2030 CO_2 emission goal (- 70%)? (If yes, how?) What does DEA include in their socioeconomic calculations for PtX? (if this has been investigated) Are there any extra considerations we need include when producing methanol to be mixed with gasoline? (Some limitations or extra costs)
"Teknologikatalog for fornybare brændstoffer" specific questions:	In chapter 98, from page 198, regarding power to Methanol, what is the electrolysis used and is it included in the presented table? Is the various storage's included? (hydrogen and Methanol) If yes, what are the storage capacities? Do you have an estimation on how the operating efficiency of the methanol reaction would be affected by a 99% purity of CO_2? What is the minimal CO_2 purity that the reactor requires? How often would the methanol reactor need to be cleaned? PtX is a technology that is commonly said to help balance the grid by having a flexible consumption. However, in the technology catalogue it says it takes 15 days to start the methanol reactor and that it operates better when it is being operated continuously. Do you have any suggestion on how we can optimise the business case for an hourly model considering this?

Table C.3: Interview question for Jacob Zeuthen from DEA. Interview conducted in Danish.

Jan Tjeerd Boom	Wednesday the 6^{th} of May 2020. **40 min. online interview**
Research Question	Question
How are socio economic calculations constructed in the central administration in Denmark?	How do Energistyrlesen calculate the socio economics for PtX in Denmark? - Is the calculation done for a specific PtX pathway (product)? - In what timeframe/scale is this investigated? - What is included in the calculation? - What is excluded in the calculation? - What future price outlook is used in the calculations? - How are CO_2 valued in the calculations? - Purchase cost and source - Emission reduction How are the environmental costs included in the calculations? - Specific inputs and values - Considerations behind these - How is the employment effect included in the calculations? - Specific inputs and values - Considerations behind these - How are importation/exportation effects included in the calculations? - Specific inputs and values - Considerations behind these

Table C.4: Interview question for Jan Tjeerd Boom from DEA. Interview conducted in Danish.

Johannes Peschko	Thursday the 7^{th} of May 2020. **5 min. phone interview**
Research Question	Question
How can excess heat from a PtX be utilised?	Can the Biogas plant utilise excess heat from the PtX plants? - How much can be utilised at the plant? - What are the temperatures?

Table C.5: Interview question for Johannes Peschko from Ride Capital Consulting GmbH

Mads Friis Jensen	Monday the 4^{th} of May 2020. **15 min. phone interview and mail correspondence**
Research Question	Question
Technology specific questions	What is the efficiency of methanol fuel cell cars? - What is the price used for methanol in a Danish context? - Is there a difference between the price of normal methanol and green methanol at the moment? (expect it to be in the future?) - What is the cost of changing a normal engine into a methanol fuel cell engine? - What are the expected changes in regards to the infrastructure for a methanol fuel cell cars? (refueling stations)

Table C.6: Interview question for Mads Friis Jensen from Blue World Technology

Morten Egestrand	Thursday the 16^{th} of April 2020. **1 hour 12 min. online interview**
Research Question	Question
How and when will PtX be utilised in Denmark?	How do you see the future of PtX in Denmark and the energy system? - Where should it be used? - What Is the timeline for this? - How is DEA working with PtX before 2030? - How is DEA working with PtX after 2030? - What is the most easily applicable PtX solution for the transportation sector? - Do PtX products play a significant role in the transportation sector in regards to the 2030 CO_2 emission goal? (If yes, how)
What are the barriers, threats for PtX in Denmark?	What do you see as the biggest framework barrier for PtX in Denmark? - How should this change? - What do you see as the biggest threat for PtX?
What are the main drivers and strength in PtX?	Who should be the main driver for PtX investments? (government, industry ect.) - What is the strength by developing PtX ? - Is there any negative side by developing PtX ?
How would DEA have the government to support PtX?	How would you envision the support towards PtX developing? Do you see a need for a subsidy? How and when should this be structured?
How should PtX support be structured in the future to reach the "basisfremskrivning" post 2030?	How would you envision the potential support towards PtX development? - Do you see a need for a subsidy? - How and when should this be structured?
What parameters are important to consider in a PtX socioeconomic analysis?	What does DEA include in their socioeconomic calculations for PtX? - What pathways (tied to the product) - Specific numbers and values Are PtX products for the transport sector compared to fossil fuel alternatives or other RES fuels?
What do you expect to be the future electrolysis developments?	- Price reduction - Efficiency increase - How widespread used is it going to be? - Is it all going to be behind the meter?

Table C.7: Interview question for Morten Egestrand from DEA. Interview conducted in Danish.

Morten Stryg	Tuesday the 10^{th} of March 2020. **30 min. face-to-face interview**
Research Question	Question
What is the stake and power of in PtX?	What is the stake and power of Dansk Energi in PtX? Does the organisation push for PtX?
How and when will PtX be utilised in Denmark?	How do you see the future of PtX in Denmark and the energy system? Where should it be used? What Is the timeline for this?
What are the barriers and threats for PtX in Denmark?	What do you see as the biggest framework barrier for PtX in Denmark? - How should this change? - What do you see as the biggest threat for PtX?
How would Dansk Energi have the government to support PtX?	How would you envision the support towards PtX developing? Do you see a need for a subsidy? How and when should this be structured?
What parameters are important to consider in a PtX socioeconomic analysis	What does Dansk Energi include in their socioeconomic calculations?

Table C.8: Interview question for Morten Stryg from Dansk Energi. Interview conducted in Danish.

Wind Power Calculations D

The methodology and calculations behind calculating the wind power generation for the behind the meter solution used throughout the Energy System Analysis are described in this appendix. Figure D.1 shows the wind speed data gathered from EnergyPRO.

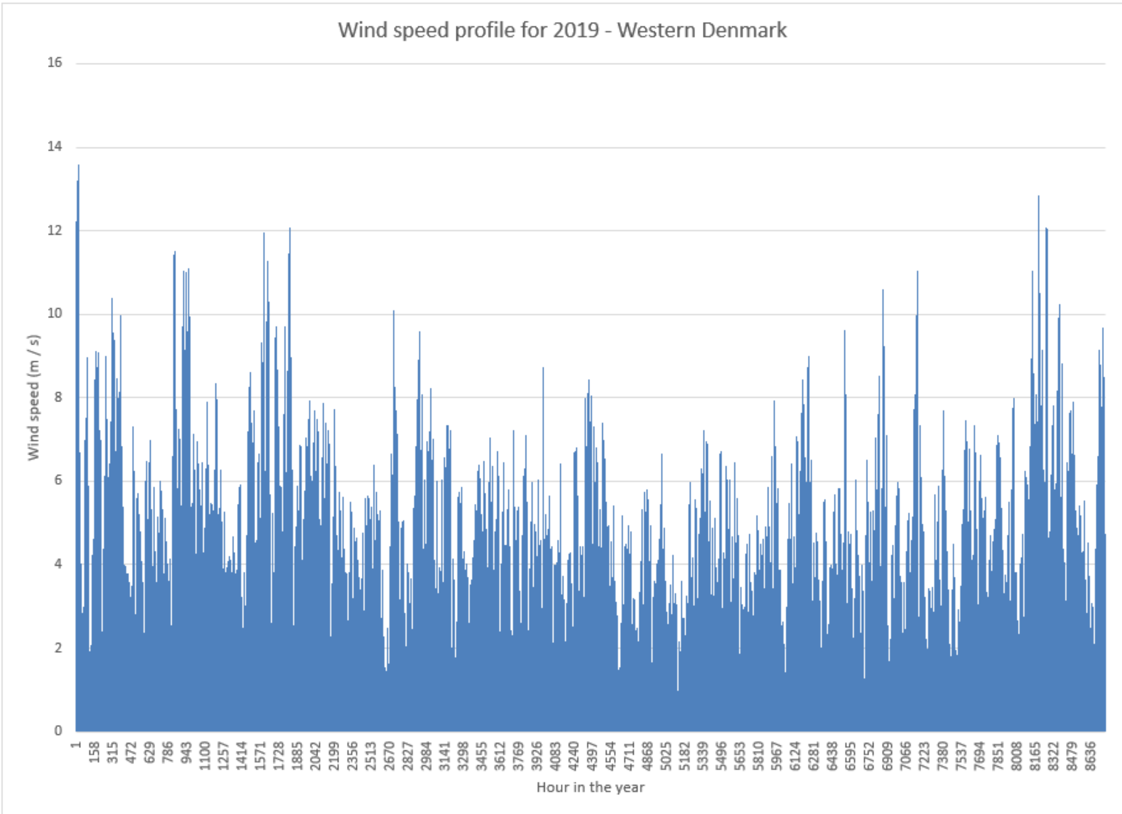


Figure D.1: Hourly wind speed data for Western Denmark, near Viborg extracted from EnergyPro. The data series chosen was CSFR 2.

The CSFR 2 data is measured at a height of 10 m and therefore the wind speed at the wind turbine's hub height has to be estimated from it. Following the calculation method. The wind turbine model used was a Vestas V136-3.45 and it was chosen for being a modern onshore model. The hub height of this model is 82 m. The formula used to calculate the wind speed at hub height can be seen in Equation D.1 obtained from (EMD International 2014).

$$WS_c(t) = WS_m(t) * \frac{H_h}{H_m}^{\alpha} \tag{D.1}$$

Where

$WS_m(t)$ = Wind speed measured (m/s) at time t

$WS_c(t)$ = Wind speed calculated (m/s) at time t

H_m = Height of measurements (m)

H_h = Hub Height (m)

α = Hellmann coefficient

The wind speed at hub height hourly values are then used in the power curve of the wind turbine to determine how much power is being generated. Firstly, a polynomial regression was made for the power curve to have a correlation between the hub speed and the electricity generation. If the wind speed at hub height is below 3 m / s, no electricity is produced in the wind turbines. If it is between 3 and 10.5 m / s, the polynomial is applied. If above 10.5 m / s, the electricity production is maximum. If above 22.5 m / s, the wind turbines have to stop and no electricity is produced. The power generation function P(t) for one wind turbine is described below:

- For $S_c(t)$ <= 3 m / s, P(t) = 0
- For 3 m / s < $S_c(t)$ <= 10.5 m / s, P (t) = -3.856586494*$S_c(t)^4$+93.7514216*$S_c(t)^3$-752.42010013*$S_c(t)^2$+2695.4752397*$S_c(t)$-3515.40662328
- For 10.5 m / s < $S_c(t)$ <= 22.5 m / s, P(t) = 3 450 W
- For $S_c(t)$ > 22.5 m / s, P(t) = 0 W

The function is scaled up to match the total wind power capacity. For example, if the total capacity is 10 MW, the P(t) function is proportionally scaled up when multiplying it by 10 / 3.45. This is applied for all hours of the year individually to calculate the wind power generation profile. The yearly profile can be seen in Figure D.2.

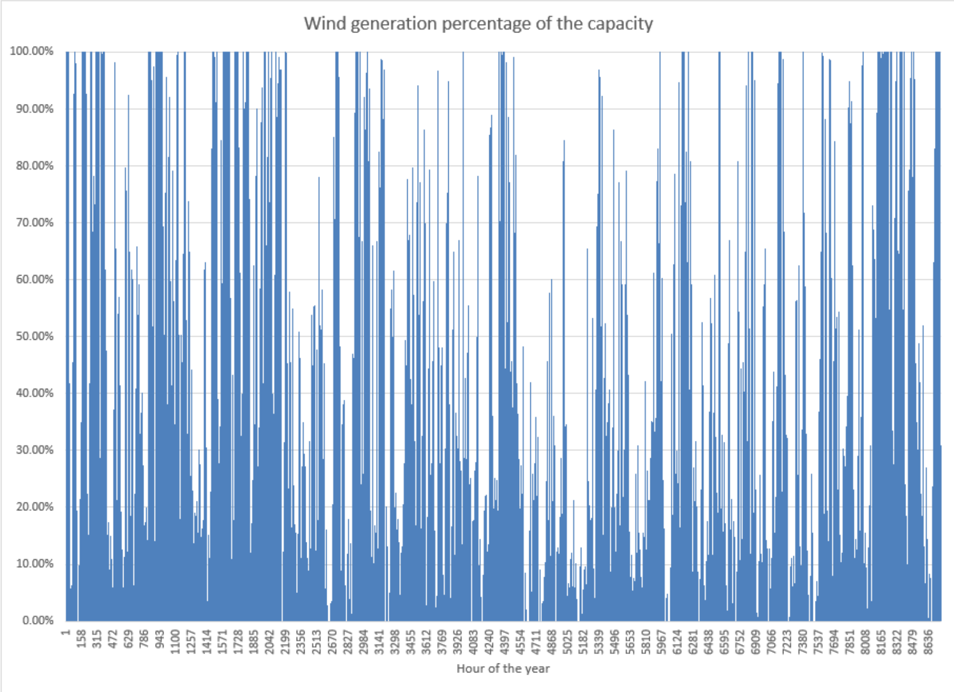


Figure D.2: Hourly wind power generation percentage over the total capacity. For example, if the wind turbines combined capacity is 20 MW, 60 % means that it is generating 12 MW electricity.