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The Feasibility of Denmark as a Potential Exporter of Hydrogen in 2045

A Socio-economic and Regulatory Framework Study

Aalborg University

Department of Sustainability and Planning

Sustainable Energy Planning and Management

Master thesis

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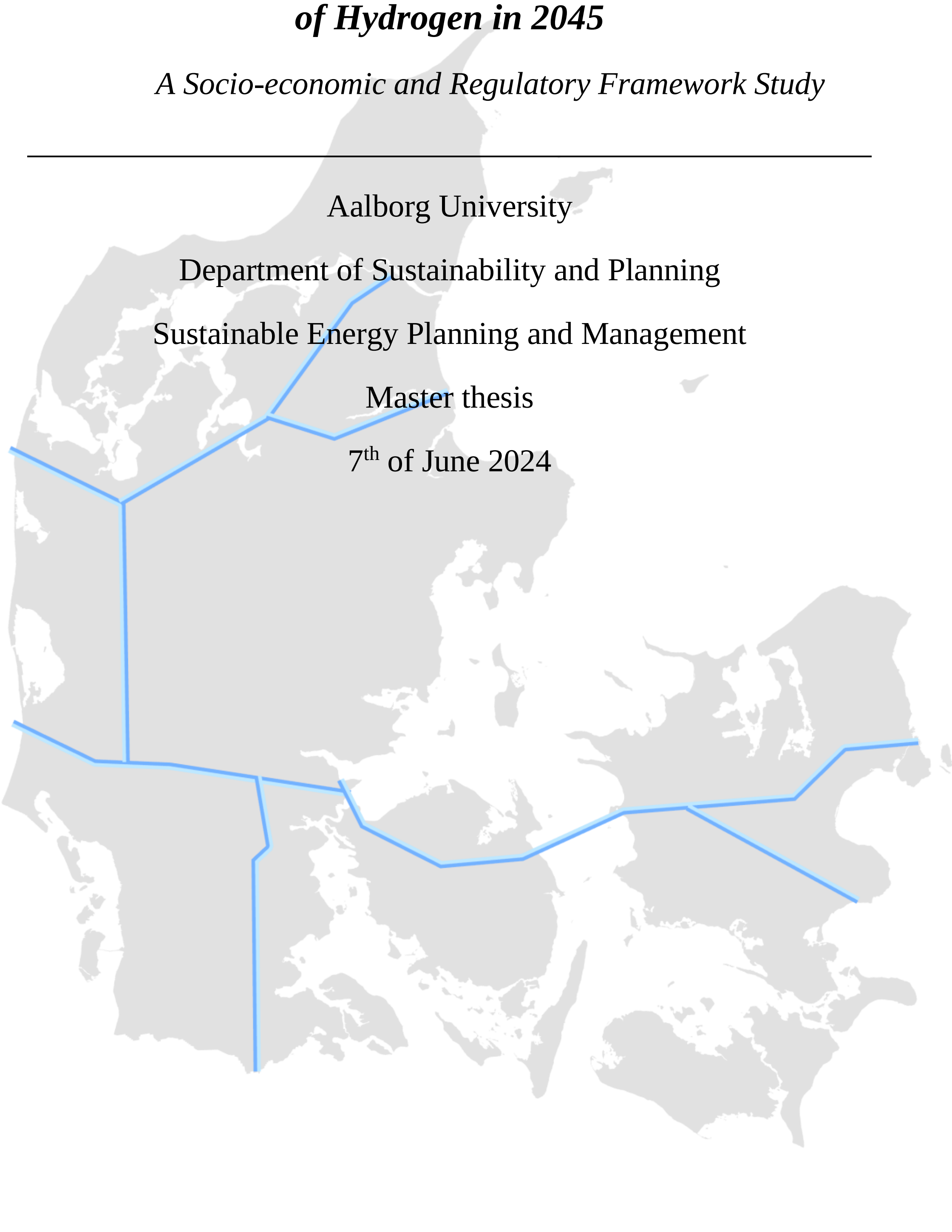

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Abstract:

Power-to-X plays a crucial role in the future energy system to accommodate the national and global climate goals. This master thesis analyses if it is socio-economic feasible to export hydrogen in Denmark in 2045 and which regulatory framework conditions should be introduced to ensure favourable planning. This is done by making three analyses; firstly, different scenarios are modelled in EnergyPLAN based on the IDA Climate Response 2045, secondly, a socio-economic evaluation is conducted for the scenarios along with sensitivity analyses, and lastly, regulatory barriers and means of actions are identified based on the technology definition and interviews with relevant Danish stakeholders. Three different scenarios have been modelled, where the operation of the electrolyser is analysed first. It is found that it is socio-economic feasible to export hydrogen when having an offshore wind capacity of 30.3 or 36.9 GW, an electrolyser capacity of 14.8 or 19.8 GW and a fixed hydrogen export demand of 54.3 or 77.85 TWh/year, which are the parameters of scenarios 2 and 3. Scenario 1 is not feasible with the given parameters. For scenario 1 to be socio-economic feasible the electricity price must be reduced by 10%, the hydrogen price must increase by 10% or the investment cost for the offshore wind turbines must be reduced by 10%. It is further found that regulation is needed for the PtX industry in Denmark before the development of PtX projects increases, and as many risks and uncertainties should be reduced as possible, by e.g. creating a favourable hydrogen market and establishing a hydrogen infrastructure.

Preface

This master thesis was carried out during the 4th semester of the master program Sustainable Energy Planning and Management at Aalborg University from the 1st of February 2024 to the 7th of June 2024.

Several interviews have been conducted to gain knowledge regarding the challenges and barriers of the Danish Power-to-X industry from different perspectives. The interviews aimed to gain more knowledge than possible from publications and get knowledge from stakeholders throughout the value chain of Power-to-X.
A thank you is directed to all the interviewees who took the time to participate in the interviews and contribute with their knowledge:

- Michael Hougaard Sandgreen, Special advisor in the PtX secretariat, the Danish Energy Agency
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Disclaimer: If statements from the interviewees are quoted or cited, they must be agreed with the interviewee.

Appendix overview:

Summary

Power-to-X (PtX) can contribute to reaching the national and global climate goals. The biggest role of PtX is to help decarbonise sectors that are difficult to directly electrify. Regulation on an EU level sets criteria for the electricity used to produce hydrogen to label it as renewable. This regulation should, however, be implemented by the individual countries. The Danish Government has made a PtX strategy for Denmark, which sets goals for the PtX capacity towards 2030, but not much action has been taken based on the strategy. Studies elaborate on the need for additional support from the Danish Government to promote the development of PtX projects in Denmark. Studies on the potential of exporting hydrogen from other countries than Denmark have been conducted, but no detailed study has been conducted on the Danish hydrogen export potential and consequences. Denmark has good conditions to be an exporter of hydrogen produced from PtX, as Denmark has good wind resources, a high security of supply, and a relatively low national hydrogen demand compared to e.g. Germany. The right amount of renewable electricity must be available and proper regulations must be introduced politically. In a report, stakeholders within the PtX business mentioned that the biggest barriers for the industry are the price of electricity, availability of electricity and alignment of the timelines for the renewable energy sources and electrolyser.

Based on this the following research question appears:

What are the socio-economic consequences of Denmark being an exporter of hydrogen, and how can the existing regulatory framework be improved to accommodate the development of PtX towards 2045?

Different theories and methods are applied to conduct the analyses in the report and answer the research question. The theory of smart energy systems is used as a general framework for the analyses and a way to understand the future energy system. The theory of choice awareness, including technology definition and radical technology change, is used combined with interviews with relevant stakeholders within the Danish PtX value chain to analyse the biggest challenges and potential means of action required to promote Danish PtX projects. To investigate the socio-economic consequences of Denmark exporting hydrogen the method of socio-economy is used including net present value (NPV) calculations and sensitivity analyses to investigate the significance of the electricity price, hydrogen price and investment cost of offshore wind turbines.

In the first analysis, the operation of the electrolyser is analysed to run based on a 75% fixed hydrogen export value and follow the critical excess electricity production. Three scenarios are analysed in EnergyPLAN, where the only electricity-producing unit changing is the offshore wind turbine capacity. The scenarios are based on the IDA Climate Response 2045, where additional electrolyser capacity, offshore wind turbine capacity, hydrogen storage capacity, and hydrogen export are changed. The baseline scenario and additional capacities of the three scenarios are as follows:

- *IDA Climate Response 2045*: 4.8 GW electrolyser, 14 GW offshore wind turbine capacity, 320 GWh hydrogen storage, and 0 TWh/year of hydrogen export.
- *Scenario 1*: 5 GW electrolyser, 9.3 GW offshore wind turbine capacity, 385 GWh hydrogen storage, and 30.75 TWh/year of hydrogen export.
- *Scenario 2*: 10 GW electrolyser, 16.3 GW offshore wind turbine capacity, 745 GWh hydrogen storage, and 54.3 TWh/year of hydrogen export.

- *Scenario 3*: 15 GW electrolyser, 22.9 GW offshore wind turbine capacity, 1106 GW hydrogen storage, and 77.85 TWh/year of hydrogen export.

Through a GIS analysis the average distance from the announced hydrogen PtX projects to an electricity transmission line and proposed hydrogen pipeline, based on the European hydrogen backbone, are analysed to be respectively 2 km and 21 km. These distances are analysed to be used in the socio-economic calculation of the investment cost of the infrastructure. The scrap value of the technologies is calculated to accommodate the different lifetimes of the technologies. The results of the socio-economic evaluation conclude that scenario 1 is not socioeconomically feasible when calculated with the economic parameters of the analysis. Scenarios 2 and 3 have a positive NPV, which represents that the scenarios are socioeconomically feasible. This can be explained by the relation between the revenue and costs being more favourable in scenarios 2 and 3 and the cost per year for producing one TWh of hydrogen for export is lowest in scenarios 2 and 3.

To investigate the impact the electricity price, hydrogen price, and investment cost of the offshore wind turbines have on the NPV, three sensitivity analyses have been conducted. The three parameters are selected to analyse, as they have the biggest influence on the NPV along with them being mentioned by the interviewees to be the main challenges. As only scenario 1 is not socio-economic feasible, the sensitivity analysis is mainly relevant for this scenario. The sensitivity analysis concludes, based on the used parameters, that for scenario 1 to be socio-economic feasible, the electricity price must be reduced by 10%, the hydrogen price must increase by 10%, or the investment cost of the offshore wind turbines must be reduced by 10%. The three scenarios are socio-economic feasible with a hydrogen price of respectively 3.3 EUR/kg, 3 EUR/kg, and 2.7 EUR/kg for scenarios 1, 2, and 3.

Based on the theory of choice awareness, including the technology definition, and several interviews with relevant stakeholders through the value chain of PtX, the main challenges and means of action are identified. The largest challenges regarding the implementation of PtX are: It is a new technology, secure renewable electricity, tariffs, offtake and the price of hydrogen, hydrogen infrastructure, business case, new and uncertain hydrogen market, regulation, timing and alignment of all processes, and general uncertainties. These challenges both represent barriers from a socio-economic point of view and a business case point of view.

Based on the analysis it is concluded that it is socio-economic feasible for Denmark to export hydrogen in 2045 when certain offshore wind and electrolyser capacities are developed. To further support the Danish PX industry, proper regulation should be implemented along with the proper framework conditions for the RE developers. The hydrogen infrastructure also has an important role to play if Denmark is to export hydrogen to the German industry.

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Abbreviations

CAPEX: Capital Expenditures

CEEP: Critical Excess Electricity Production

COD: Commercial Operation Date

DA: Delegated Acts

EU: European Union

FLH: Full Load Hours

GHG: Greenhouse Gasses

LCOH: Levelized Cost of Hydrogen

NGO: Non-Governmental Organisation

NPV: Net Present Value

PtX: Power-to-X

PV: Photovoltaic

RE: Renewable energy

RED: Renewable Energy Directive

RES: Renewable Energy Sources

RFNBO: Renewable Fuels of Non-Biological Origin

SAF: Sustainable Aviation Fuel

SES: Smart Energy System

TSO: Transmission System Operator

1 Introduction

Human activities through emissions of greenhouse gasses (GHG) have caused global warming where the use of fossil fuels is one of the major contributors. According to the latest IPCC report on climate change, it is likely that global warming will exceed 1.5 °C during the 21st century which makes it more difficult to limit global warming below 2 °C [1]. The goal of limiting the increase in the global average temperature below 2 °C and preferably below 1.5 °C was agreed in the Paris Agreement from 2015 by 196 parties at the UN Climate Change Conference [2]. If the temperature is kept below 1.5 °C the impacts and risks of climate change are reduced [2].

Fossil fuels are the largest contributor to global warming and constitute above 75% of GHG emissions and almost 90% of all CO_2 emissions [3]. The energy sector has huge reduction potentials if fossil fuels are replaced by sources based on renewable energy (RE) as this sector primarily is based on fossil fuels [3]. RE is in this report based on the definition from the IPCC [4] which states "*RE is any form of energy from solar, geospatial or biological sources that is replenished by natural processes at a rate that equals or exceeds its rate of use*". The included renewable energy sources (RES) from IPCC are thereby wind, solar, bioenergy, hydropower, geothermal heat, and wave energy.

When designing the future energy system new paradigms have appeared such as 4th generation district heating, smart grids, and power to gas. It is, however, important to see the new paradigms from a greater perspective and in the context of the overall energy system. When planning future energy systems, the smart energy system (SES) concept is introduced. SES includes the entire energy system when planning for new development and infrastructure. The benefit of SES is that the advantages and disadvantages of different sectors can be integrated to even out the disadvantages. This can e.g. be seen when the electricity sector is combined with the heating or transport sector, as the future energy system is mainly based on fluctuating electricity production from RES. The SES concept is planning for the entire energy system where the integration and symbioses of all sectors are considered instead of making separate planning for the individual sectors. [5]

To meet the global climate goals and to transit towards an energy system based on 100% RES, national plans are conducted for several countries [6]. An example of a country with national goals is Denmark, where the Danish Government has made the goal of reducing the Danish GHG emissions by 70% in 2030 compared to 1990, and that Denmark should be climate neutral no later than 2050, where the goal from the Paris Agreement is the foundation [7]. The Danish Government do, however, want to advance the last goal to be met by 2045 [8]. Denmark is one of the countries with the highest CO_2 emissions per capita, but the energy policy has already led to a decrease in emissions [9].

One of the most important strategies in reaching global and national climate goals is electrification. Electricity can to a high extent replace fossil fuels in several sectors such as in the transport, industry, heat, and power sectors [10]. It is, nevertheless, important that the electricity is produced by RES [10]. There are some challenges connected to the increase in the electricity demand such as the need to expand the power grid [10]. When an energy system is based on production from RES, technologies or measures must be included to balance the fluctuation in the production such as storage or sector coupling [11]. Sector coupling and indirect electrification are especially important in sectors, that cannot be directly electrified [12]. Indirect electrification is defined as the conversion of electricity to hydrogen or hydrogen-based fuels [12]. Heavy-duty transport, agriculture and some industrial processes cannot be directly electrified and are thereby dependent on indirect electrification [13]. A solution to the sectors that cannot be directly electrified is Power-to-X (PtX) [14].

2 Problem Analysis

This chapter identifies the role and status of PtX in Denmark and highlights the problem the report and analysis are based on. Furthermore, the current EU regulation related to PtX is presented and the needed electricity. The concept of PtX is also presented along with predictions and goals within the renewable energy sector. The role of hydrogen and PtX in the future is highlighted and the needed supporting hydrogen infrastructure is described. The different challenges and roles of PtX in Denmark are identified based on literature reviews to get an overview of the potential barriers within the industry.

2.1 EU Regulations and Legal Framework

The PtX industry is regulated by the government of the given country and also regulated by the European Union (EU) which sets policies for the industry and for the greater good of Europe [15].

The EU is the main institution of the European member countries which addresses the shared interests between the member states. The institution of the EU consists of 7 administrations that each have specific roles, from the planning and development of laws and regulations to implementing these new policies. These administrations or institutions include the European Parliament, the European Council, and the European Commission. These institutions cooperate with the institutions of each member country. [16]

Market participants have been waiting for an exact definition of renewable fuels to secure their renewable hydrogen production. This was cleared when the European Commission revised the Renewable Energy Directive II (REDII) and proposed two delegated acts (DA) for renewable fuel and renewable electricity requirements. [17]

In 2009 the EU set out the Renewable Energy Directive I (RED I) whose purpose was to plan and implement the legal framework for the continuous development of renewable energy (RE) in every energy sector across the member countries of the EU. The RED I was revised in 2018 and the new RED II was published. The goal of the RED II is to support the transition of the energy consumption of the EU to more RE to accommodate the goal of 32% RE in 2030. The RED II was revised in November 2023 and REDIII was implemented. Following the REDIII, the RE targets have been updated to fit the current status and societal perspectives. The new RE targets are aiming for at least 42.5% RE in 2030 but hopefully accomplish a RE share of 45% in the energy consumption in the EU. The latest targets are among others forced from the invasion of Ukraine, as the independence of fossil fuels is intensified. [18]

Following the implementation of RED III, two Delegated Acts were introduced by the European Commission [20], [21]. The main focus of the DA is to define what categorises renewable hydrogen, and as to which conditions must be in place for the hydrogen to be renewable [22]. The objective is to ensure that the increase in the hydrogen demand in the EU correlates with the installation of new RE [22]. The first DA makes the definition of when renewable fuels of non-biological origin (RFNBO) including hydrogen and hydrogen-based fuels can be considered renewable. The definition of RFNBO is included in the RED II [19]. The first DA categorises the RFNBO to be renewable when they are produced from other sources than biomass, and when the electricity used is from renewable sources [20]. Hydrogen that is produced in an electrolyser with the input of RE can be categorised as an RFNBO, and likewise, other e-fuels such as ammonia, and methanol can be categorised as RFNBO if they are produced from renewable hydrogen [20]. An important aspect of the RFNBO is that they must have a minimum of 70% saving of GHG emissions compared to fossil fuels to contribute to the renewable targets of the EU. The exact methodology of defining and calculating the GHG savings of the RFNBO is included in the second DA [22]. The calculation of GHG savings must include the full life cycle of the producing RFNBO [21].

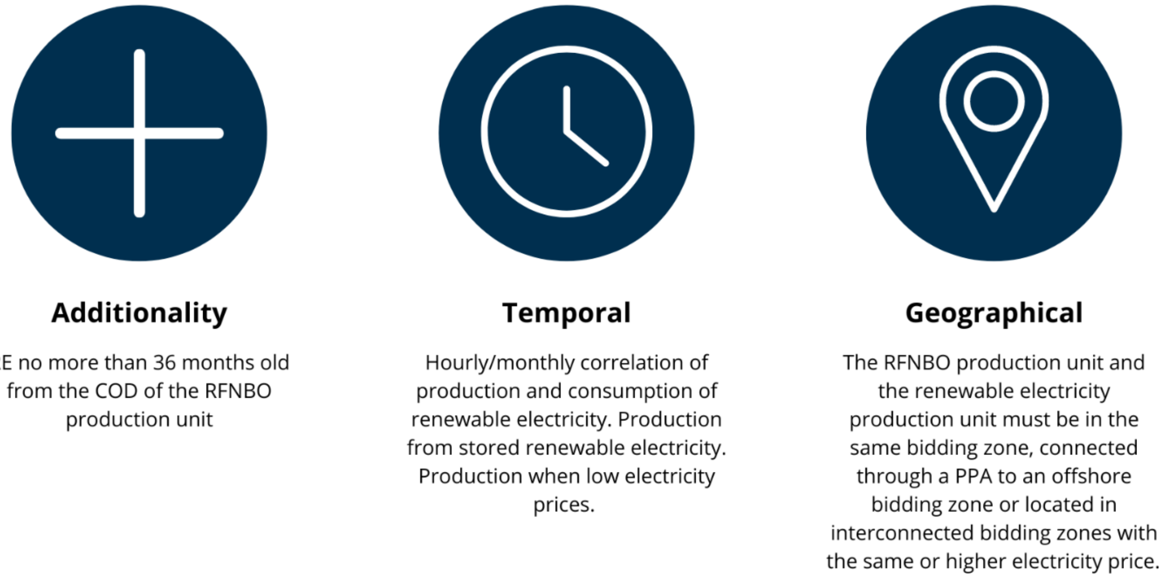


Figure 1: The three criteria set out in the first DA regarding renewable electricity for the production of RFNBO [20].

The first DA sets criteria for renewable electricity production to support the production of RFNBO. The three criteria are visualised in the above *Figure 1.*

All of the above-mentioned criteria also apply to the production of renewable hydrogen produced outside of the EU, which is imported into the EU. [22]

Through both the RED II and the respective first and second DA different options for sourcing renewable electricity are presented, all complying with the three criteria. One option is to source renewable electricity from a direct connection from the electricity production unit to the RFNBO production unit, with no connection to the electricity grid. In this option, it is demonstrated that the electricity used is from this exact production unit and that it is renewable. Whereas, when the electricity production unit is both connected to the electricity grid and the RFNBO production unit, it is essential to provide evidence that the electricity used comes solely from the direct connection [20], [23]. In coherence with the first DA, one of the options of receiving electricity from the electricity grid and simultaneously maintaining the regulations that follow the RFNBO is to ensure that the respective electricity grid and its bidding zones have a minimum share of 90% renewable electricity in the previous year. This ensures that the 70% reduction in GHG savings compared to fossil fuels is kept [20]. Another way of assuring that the electricity from the electricity grid is categorised as renewable is to confirm that the emission intensity of the electricity is below 18 gCO_2eq/MJ to comply with the criteria of the RFNBO having a minimum of 70% GHG savings compared to fossil fuels [20]. In these two options where the electricity grid either consists of a minimum of 90% renewable electricity or with an emission intensity of electricity below 18 gCO_2eq/MJ, it is not necessary to comply with the criteria of additionality [20]. The final option of sourcing renewable electricity from the grid is to consume electricity in times of imbalance in the electricity grid to reduce the need for dispatching [20].

To ensure renewable electricity to the RFNBO producing units it is essential to investigate the concept of PtX and the needed electricity in the process.

2.2 The Concept of PtX and Needed Electricity

To meet both the global and national climate goals PtX plays a crucial role as all sectors cannot be directly electrified [12]. An example of an industry which heavily relies on hydrogen is the German industry, and Germany is also dependent on imported hydrogen due to their large demand [24].

When referring to PtX in this report it is assumed that the process is based on RES even though the process also can use electricity based on fossil fuels. PtX covers the concept of converting renewable-produced electricity to a variety of products. Water is split into hydrogen and oxygen through electrolysis powered by renewable electricity, whereafter the hydrogen can be the end-product or converted even further to other fuels such as methanol and ammonia. To produce methanol a biogenic CO_2 source is needed and to produce ammonia, nitrogen from the atmosphere is needed. [25]

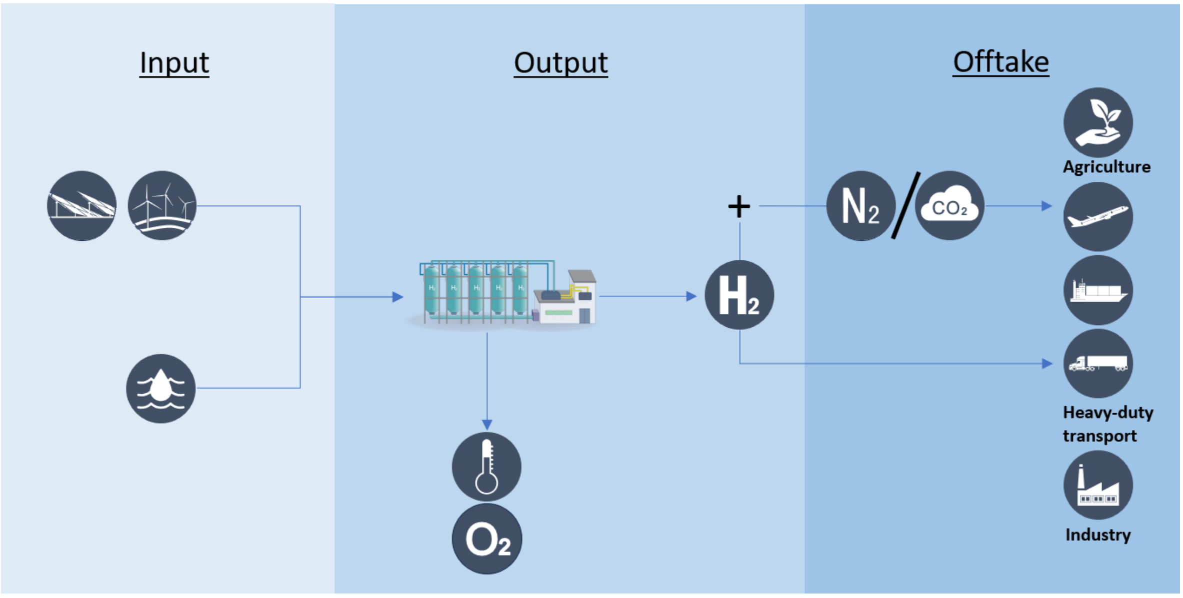


Figure 2: Overview of the PtX process.

As seen in *Figure 2* the input of the electrolyser is electricity from RES and water, where it is necessary, that the water is of high purity. The output is hydrogen, oxygen, and excess heat. The oxygen can be used in several sectors such as paper production, water oxygenation, steel, medical care, food etc. and the heat can be used for district heating. The hydrogen output can be the final fuel or converted even further to other fuels. [26]

There are three primary types of electrolysers today: Alkaline electrolysis cells (AEC), proton exchange membrane electrolysis cells (PEM), and solid oxide electrolysis cells (SOEC). The AEC is the most mature and common electrolyser type.

Year 2040	AEC	PEM	SOEC
Electricity input	100%	100%	81.4% (the rest is heat)
Efficiency	71.5%	68%	82%
Hydrogen (kg/ MWh $input_e$)	21.5	20.4	24.6
Lifetime (years)	32	28	20
Space requirements (m^2/MW $input_e$)	8	20	15
Startup time after long shutdown (cold start-up time) (min)	120	10	720
Startup time from stand-by mode (warm start-up time) (sec)	240	10	900

Table 1: Electrolyser characteristics of 1 MW electrolyser [27].

As seen in *Table 1* the SOEC electrolyser is the most efficient in 2040, but this electrolyser technology is not as mature and on a commercial scale yet, and one of the disadvantages is, that SOEC has much longer start-up times than AEC and PEM [26]

One of the largest roles of PtX is to help decarbonise sectors that are difficult to directly electrify [14]. A downside is that the products from PtX have generally a relatively high price compared to the alternatives based on fossil fuels [14]. PtX also provides flexibility to the energy system which is an important aspect, as the RE demand increases in the future energy systems along with an increase in the electricity demand, so PtX can help balance the intermittence and fluctuations from the RES [28].

The common electricity production units of renewable electricity for PtX plants are onshore and offshore wind turbines and photovoltaic (PV), which are supplied to the PtX unit either from the electricity grid or from a direct line [29]. It is often addressed that an advantage of PtX plants is that they can harness the surplus electricity from renewable electricity production, but the PtX plant also needs a baseload of electricity production to have a feasible production [30]. In 2018 the Danish wind turbines only had an excess production of electricity of 1,238 hours, which is equivalent to the PtX plant only producing hydrogen in 14% of its operating hours which will not make a feasible business case nor will it reach the demand for hydrogen and other e-fuels in the future [30]. The low operational loads of the electrolyser based on excess electricity that are associated with fluctuating electricity production create challenges for its operation and the efficiency of the plant [31]. The study of Amireh et. al [31] analyses the efficiency of both AEC and PEM electrolysis in correlation with fluctuating electricity, and concludes that they both will suffer losses in efficiency of 1.2%-1.5% at full load and 5.6%-10.6% at part load of 20% [31]. This indicates a higher efficiency loss when operating at part loads. A study by Berg et al [30] on the role of PtX when excess wind energy is available in Denmark has also been conducted and concludes that it is not economically feasible to invest in PtX with the sole purpose of operating according to excess electricity.

The production profile of wind turbines both offshore and onshore, and PV are fluctuating which means that there in some hours will be little to non-production from these units because they are relying on sun and wind resources [29]. This uncertain production profile of wind and PV creates a discrepancy between the demand and supply of electricity, and makes it difficult to determine a production profile for the PtX plant, as it to produce renewable hydrogen is committed to using renewable electricity [29]. This means, that to obtain a consistent production profile of the PtX plant, new strategies or other RES are to be found in hours with low production from wind turbines and PV [30]. A strategy could be to initiate PPAs with renewable electricity production units [32].

The study of Hofrichter et al [33] investigates the economically optimal ratio between the installed electrolyser capacity to RES capacity, with the point of departure in wind and PV. The study aims to give PtX developers the possibility to construct PtX plants with a cost-optimised design and electricity source. An optimal electrolyser-RES-ratio is dependent on the location of the RE production and the weather conditions alongside a high installed capacity of RES. The most important factor is the full load hours (FLH) of the RES, as high FLH will contribute to a low hydrogen price. The higher the ideal electrolyser-RES-ratio is, the lower the hydrogen production cost is and the lower the levelized cost of hydrogen (LCOH) is. The results of the electrolyser-RES-ratio analysis show that wind power is the more favourable RES, compared to PV, as it provides better conditions to produce hydrogen. The analysis shows that wind power operating at low FLH can compete with PV installations operating at high FLH. It is also stated that onshore wind turbine sites with good wind resources can compete with offshore wind turbine sites. [33]

There is no ideal electrolyser-RES-ration that can be applied to all cases, the ratio is very dependent on the individual design of the PtX plant and especially the location of the plant [33]. The power input of the electrolyser is in the study of Hofrichter et. al [33] determined according to the power from the RES.

There is also the discussion of whether the RES for the electrolyser should be with an off-grid production or an on-grid production. The definition of off-grid production is that the RES is not connected to the electricity grid, neither the transmission nor the distribution electricity grid, it is just connected to the electrolyser, compared to an on-grid connection where the RES is connected to the electricity grid. The study by Pratchner et. Al [34] presents a techno-economic assessment of off-grid vs. on-grid options for a power-to-liquid plant. The study concludes that the main expenditure of a Fischer-Tropsch electrolyser plant of 1 MW, which is connected to the grid, is capital expenditures (CAPEX) and the price of electricity, with a respective share of 30% and 50%. In a scenario of a 100 MW Fischer-Tropsch electrolyser plant, connected to the grid, the expenditure share of electricity price is up to 88%. The scenario with on-grid RES resulted in a hydrogen production cost of 2.42 to 4.56 EUR/kg with 2022 numbers. The off-grid RES resulted in a hydrogen production cost of 1.28 to 2.40 EUR/kg, with onshore wind and PV electricity production at a level of 2.40 EUR/kg, and offshore wind power at a level of 1.85 EUR/kg. The cost parameter that makes the difference in the on-grid and off-grid scenarios is the net production cost related to e.g. net tariffs. The hydrogen production cost is expected to decrease towards 2050 as reductions in the electrolyser's fixed investment cost and the levelized cost of RES are expected. [69]

As PtX requires a lot of electricity this is an important aspect of a PtX project, and the ratio between electricity and PtX is essential if climate goals are to be met. When planning the future energy system an important factor is the goals and predictions for the amount of available electricity based on RES.

2.3 Predictions and Goals for the Danish Electricity- and PtX Production

The Danish Government has goals for the development of RES in Denmark. Likewise, the Danish Energy Agency has made predictions for the development of RES in the future. Furthermore, a study has been conducted by scientists from Aalborg University in collaboration with the Engineers' Association in Denmark (IDA), which is a proposal on how Denmark can meet its 2030 climate goal and be climate neutral in 2045 [35]. In this study, the proposed energy system is modelled in the energy system modelling tool EnergyPLAN. To reach climate neutrality in 2045 the study estimates an electrolyser capacity of 4,8 GW, 5 GW onshore wind, 14 GW offshore wind and 10 GW solar panels on roofs are necessary [35]. The goals and predictions of the RES production capacity in 2030 and 2045 are shown in below *Table 2.*

The Danish Government and eight other political parties have on the 15th of March 2022 agreed on the goal for the Danish PtX capacity in 2030 of 4-6 GW [36]. The Danish Ministry of Climate, Energy and Utilities published the goal of implementing 9-14 GW offshore wind capacity before 2030 through the largest offshore wind tender in Danish history on the 30th of May 2023 [37]. On the 22nd of April 2024, the Danish Energy Agency published, what they call, the biggest wind tender in the Danish history of a 6 GW offshore wind turbine capacity [38]. The winners of the tender areas are, however, allowed to utilize the area to produce more than the suggested 6 GW, as it is estimated that there is a potential to install up to 10 GW [38]. The additional electricity produced is predicted to accommodate the higher demand for electricity for PtX [38].

The Danish Ministry of Climate, Energy and Utilities published a note in October 2023 announcing the expansion of PV and onshore wind turbines. The goal is to quadruple the total production of both PV and offshore wind turbines towards 2030, it is, however, not mentioned which year the quadruple takes its point of departure. [39]

The Danish government complied in 2022 with the Esbjerg Declaration, which is a declaration between Denmark, Belgium, Germany, and the Netherlands to ensure offshore wind development in the North Sea. The Danish government is through the declaration committed to reach at least 10 GW capacity of offshore wind in 2030, and up to 35 GW by 2050 in the North Sea. [40]

Predictions for RES capacities in 2030 and 2045 are found in the Analytical Prerequisite Document the Danish Energy Agency has made for Energinet [41].

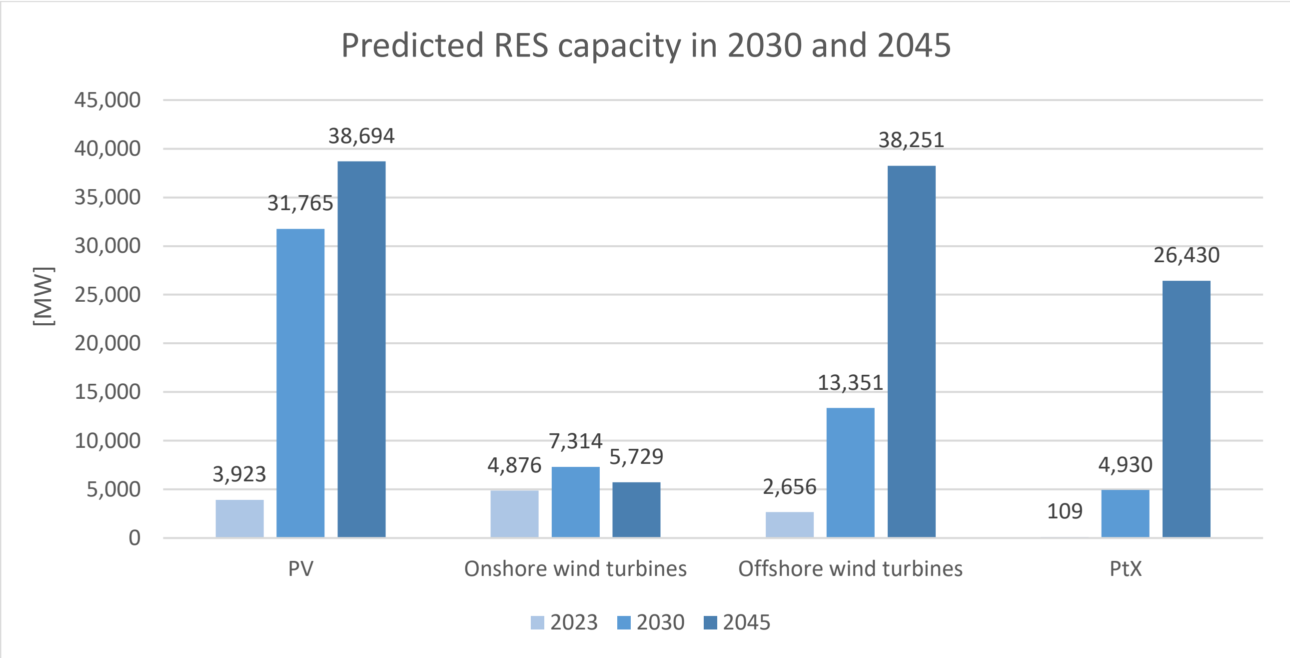
Exact numbers on the PV, onshore wind and PtX capacities for 2045 have not been published by the Danish Government which is why the fields in the below table do not contain any numbers.

Year	PV	Onshore wind	Offshore wind	PtX
2023 status	3.9 GW [41]	4.9 GW [41]	2.7 GW [41]	0.1 GW [41]
2045 IDA predictions	10 GW [35]	5 GW [35]	14 GW [35]	4.8 GW [35]
2030 political goals	Quadruple [39]	Quadruple [39]	9-14 [37]	4-6 [37]
2045 political goals	-	-	35 GW (2050) [40]	-
2030 predictions	31.8 GW [41]	7.3 GW [41]	13. 5 GW [41]	4.9 GW [41]
2045 prediction	38.7 GW [41]	5.7 GW [41]	38.3 GW [41]	26.4 GW [41]

Table 2: Predictions of renewable energy production capacity in the years 2030 and 20245 [41].

2.3.1 Analytical Prerequisite Document for Energinet

The Danish Energy Agency published an analytical prerequisite document for the Danish transmission system operator (TSO), Energinet, on the 31st of October 2023, to outline the predicted development of RES towards 2050 [41]. The document gives a likely estimate on the development of the part of the Danish energy system that is of relevance to Energinet. The document focuses on the development of electricity production capacity, transmission connections to other countries, the consumption of electricity and gas, and the production of hydrogen from electrolysis [41]. In the prerequisite document, the Danish Energy Agency includes the development of technologies and assumes that political policies and goals are achieved, which means that the predicted development is not based on a frozen policy scenario [41]. The prerequisite document is therefore based on the basis that the Danish political goals are going to be fulfilled, this includes the goal of reducing 70% of the Danish GHG emissions in 2030 compared to levels of 1990, and the goal of 100% climate neutrality by 2050 [41]. The following Graph 1 gives an overview of the predicted RES capacity in 2030 and 2045, and the capacity in the year 2023 for comparison.



Graph 1: Graphic overview of the predicted RES capacity towards 2030 and 2045 from the analytical prerequisite document from the Danish Energy Agency [41].

The offshore wind capacity is based on goals from the Esbjerg Declaration [40] stating to exploit the full wind potential of the Danish North Sea towards 2050. After the year 2040, the plan is that half of the newly installed capacity of offshore wind turbines will be connected to the electricity grid of Denmark, equivalent to 7.5 GW [42]. The other half is predicted to be hydrogen turbines with a hydrogen production equivalent to the FLH of the individual turbines [42]. The hydrogen production from the hydrogen turbines is expected to be exported to the European hydrogen infrastructure [42]. The PV and onshore wind resources are based on the political goal of quadrupling the production towards 2030 [39]. The PV resources are split into units on fields and rooftops and the expansion will continue towards 2045 [43]. The expansion of onshore wind turbine capacity after 2030 is based on the prediction that the electricity demand for onshore wind turbines is consistent and doesn't increase, which means that there will not be further expansion of onshore wind turbines after 2030 [43].

The capacity of electrolysis and production of hydrogen in the prerequisite document is based on the expansion and production of renewable electricity from wind resources in the Danish North Sea. The expansion of PtX capacity will follow the expansion of offshore wind capacity [41]. The electricity for the PtX capacity will mainly be provided by offshore wind turbines [43]. The produced hydrogen in the document is divided into the consumption in Denmark, the consumption towards international transport and the export of hydrogen and other PtX-products [41]. The prediction is that Denmark will be a big exporter of PtX-products in the long run, this includes hydrogen, methanol, ammonia, and other e-fuels [41]. The export capacity is presented in produced hydrogen but includes other PtX-products [44]. The increase in electricity production towards 2030 and 2045 can therefore be explained by the high PtX capacities that accommodate an export of PtX products.

The electricity production capacity has a large increase towards 2050 according to the prerequisite document. This is due to the general electrification of society towards the goal of climate neutrality in 2050, the export of electricity to the rest of Europe due to balancing, and the increased electricity consumption from electrolysers.

The total predicted capacity of offshore wind in 2045 also includes the two Energy Islands, one in the Danish North Sea and one near Bornholm, where the predicted capacity of the two is 13.4 GW in 2045, and the energy island in the Danish North Sea has a predicted capacity of 10 GW in 2045 [41]. When including the capacity of the Energy Islands, it is relevant to acknowledge that the planning of the North Sea energy island is currently on hold due to a poor business case for the Danish Government and that the commercial operation date (COD) might be later than expected [45], [46].

Electricity plays a crucial role in the development of PtX, as this is one of the inputs in the electrolyser, and the price of electricity influences the entire business case. Large amounts of electricity are needed in the future energy system to accommodate the generally increasing electricity demand and the indirect electrification to PtX.

2.4 PtX in the Future Energy System

As mentioned in *section 2.2* PtX plays an important role in the future energy system to meet the climate goals. Different countries do, however, have different opportunities and challenges, when it comes to the production of PTX, and export is therefore also important if the world is to meet the global climate goals.

2.4.1 Export of Hydrogen and the Hydrogen Infrastructure

Hydrogen can be transported by ships, trucks, trains, and pipelines. For longer distances, hydrogen is often transported by pipelines or ships. The export of hydrogen will often happen when the exported hydrogen is cheaper than locally produced hydrogen when also considering the transportation cost. Hydrogen is also often transported when the consumption and generation are not in the same location. [47]

From a European point of view, a European Hydrogen Backbone report has been conducted by 33 energy infrastructure operators including Energinet, the Danish TSO [48]. It states that cross-border infrastructure, including hydrogen pipelines, is crucial in the energy system. The hydrogen infrastructure enables large-scale development of PtX projects and the production of hydrogen in zones, where the costs are low. Hydrogen pipelines of 31,500 km are expected commissioned before 2030 managed by the reports TSO members and the TSOs are actively seeking sufficient contractual commitment from future users of the hydrogen pipelines to support the investments. [48]
The proposed hydrogen infrastructure in Denmark can be seen in *Figure 3.*

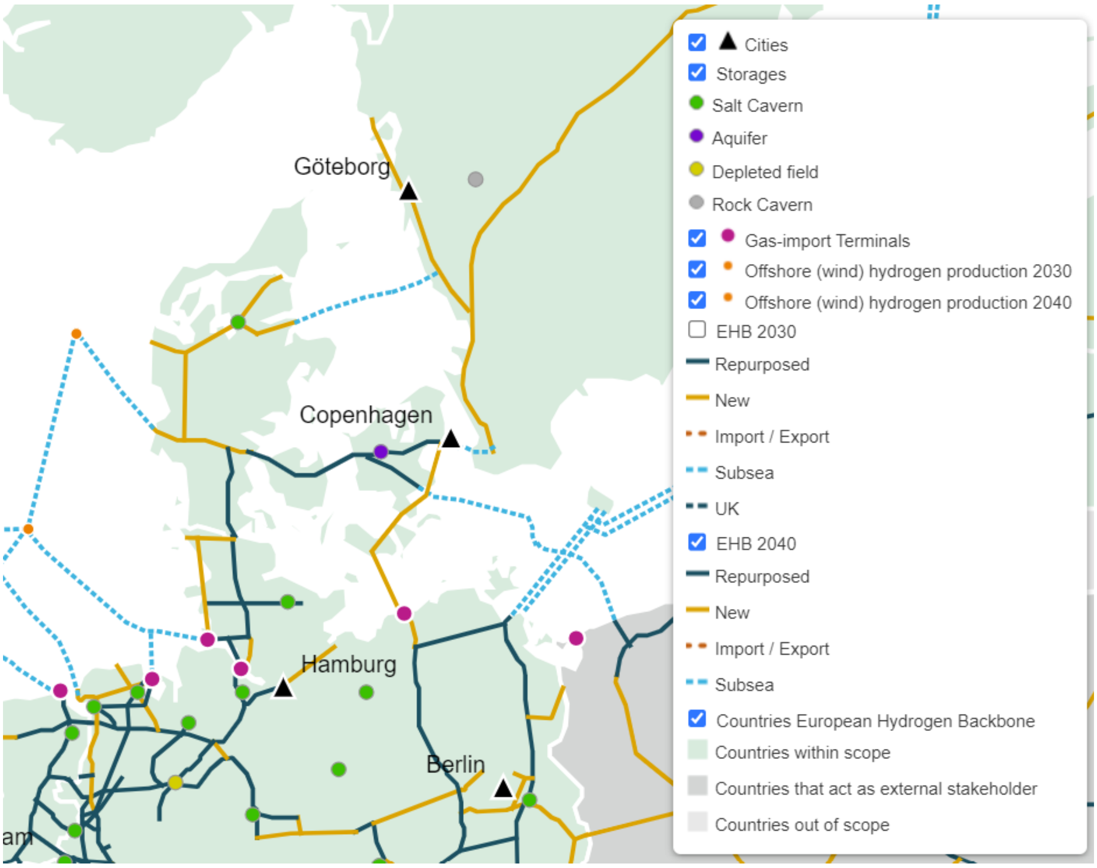


Figure 3: European Hydrogen Backbone Map [49].

The western Danish pipeline is expected to transport up to 10 GW of hydrogen from Denmark to Germany and the offshore wind turbines also play an important role in the Danish part of the project [48]. On the 22nd of May 2023, the Danish Government published an agreement document regarding the ownership of the Danish hydrogen pipeline and the principles for establishing the hydrogen infrastructure in Denmark. In this publication, it is stated that establishing a hydrogen pipeline in Denmark supports the export of hydrogen to Germany. Energinet, the Danish TSO, and Evida, the Danish gas distribution operator, should be the owners of the hydrogen pipeline, where the role of Energinet amongst others is to be in charge of the hydrogen pipelines from Denmark to other countries, and the role of Evida is the domestic hydrogen pipelines. [50]

The hydrogen pipeline, which Energinet currently is conducting feasibility studies for, is not as large as the European Hydrogen Backbone pipeline, as it stops at Lille Torup, which is marked as a salt cavern in the North of Jutland in *Figure 3* and does not continue north [51]. As Energinet is also a part of the European Hydrogen Backbone report, it is however assumed, that they investigate expansions of the pipelines in the future, when a hydrogen pipeline is developed.

A techno-economic analysis of green hydrogen export has been conducted by Makepeace et al [47], which found that 85% of the green hydrogen will have to be transferred between regions to achieve the most economically optimal distribution. The study found that the hydrogen prices will be higher in Europe and Asia, and these regions will generally import green hydrogen, whereas Australia, South America, North America and Africa are projected to be exporters. [47]

Another techno-economic study has been conducted by Gallardo et al [52] This study analyses hydrogen produced by PV in Chile and the exportation to Japan by ship. The LCOH is calculated for different scenarios where both liquified hydrogen and ammonia have been included. The study found that the most cost-competitive production in Chile is by making a PV PPA and including an AEC electrolyser, where the LCOH reached a price of 2.20 USD/kg in 2018 and 1.67 USD/kg in 2025-2030. The study also found that the cost of electricity has a paramount importance on the LCOH compared to the CAPEX price. [52]

A study with another objective is conducted by Tyguin et al [53]. This study examines the public acceptance and effects of hydrogen export focusing on economic and environmental framed messages. The way hydrogen export is framed impacts public acceptance as different perceptions appear based on whether the focus is on the economy or the environment. The study found that the public acceptance of hydrogen produced by RES is higher than hydrogen produced by fossil fuels. The study also found, that there is a marginally higher level of public support when the focus is on the environment instead of economics. [53]

Several studies have been conducted on different countries such as Saudi Arabia [54], Canada [55], Colombia [56], Norway [57] and Australia [58] on the export of hydrogen, but no academic detailed analysis has been conducted for Denmark.

According to the Danish hydrogen industry, Denmark can cover 25% of the German hydrogen import demand, by dedicating 3-3.5 GW electrolyser capacity to export [59]. The Danish TSO has also made estimates on the produced hydrogen and the consumed hydrogen in Denmark [60]. As seen in Figure 4 the predicted hydrogen production is larger than the estimated consumption after 2025. The excess produced hydrogen can be exported to other countries.

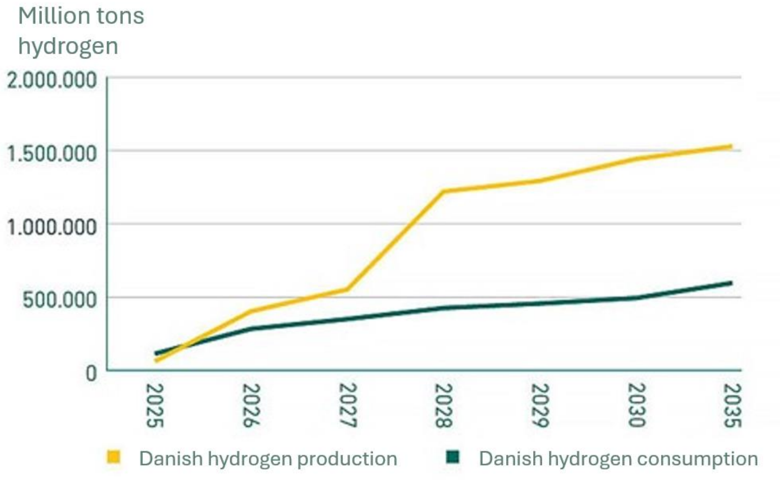


Figure 4: The Danish hydrogen production and consumption [49].

One of the Danish Government's four means of action to advance PtX in Denmark in the PtX strategy is that Denmark should be able to export PtX products and technologies. The export of PtX fuels can create growth and workplaces in Denmark, while also reducing GHG emissions outside Denmark's borders. The Government wants to make an investment support scheme to contribute to the upscaling and development of PtX technologies and strengthen the framework to secure access to financing of large-scale PtX projects. The Government also wants to strengthen the framework for Danish companies to export certified sustainable hydrogen and other PtX fuels and establish a hydrogen infrastructure in Denmark so the hydrogen can be exported to other countries. It is important, if Danish hydrogen is to be exported competitively, that the Danish hydrogen infrastructure is connected to the planned coming European hydrogen infrastructure. Some of the existing natural gas pipelines can potentially be used for this purpose. [61]

Energinet and Gasunie, who maintain the German gas infrastructure, have on the 16th of November 2023 signed a collaboration agreement to secure the expansion of the hydrogen pipelines between Denmark and Germany so it in 2028 is ready to transport Danish-produced hydrogen from RES to German hydrogen consumers. The hydrogen pipeline is expected to be from the planned hydrogen storage in Lille Torup to Heidenau south of Hamburg, with a combined length of 550 km. [62] Even though the agreement is signed, no Danish financing strategy or detailed plan for the project is presented. This creates uncertainties for the development of wind and PV projects, as it does not make sense to develop large-scale wind and PV projects if no large-scale PtX plants are planned, which can be the result of no hydrogen infrastructure as the hydrogen cannot be transported. The wind and PV developers need certainty regarding the hydrogen infrastructure to know if it is feasible to convert the electricity to hydrogen. [63]

Several countries such as Germany, the Netherlands and Belgium want to import hydrogen and other PtX fuels, which makes the export of PtX fuels from Denmark a good opportunity as the demand exists. The mentioned countries have a large consumption of fossil-based hydrogen today, but this can be replaced by hydrogen produced from RES. The 4-6 GW electrolyser goal must support the Danish export potential of PtX fuels, but the PtX strategy does not further describe how much of the hydrogen should be converted to e.g. methanol or ammonia. [61]

Denmark has good prerequisites to be an exporter of PtX fuels, as there are excellent RE resources, high security of supply, good competencies throughout the entire value chain of PtX and a well-connected power grid to other countries. To incentivize the production of fuels from PtX, governmental support and regulation are needed to lower the prices along with proper framework and conditions. [17]

As PtX requires a lot of electricity this is an important aspect of a PtX project, but even if there is enough electricity for PTX, the role and challenges of installing a PtX plant are important to keep in mind when planning the future energy system. When the challenges are identified it is possible to overcome some of them and plan a PtX project beneficial to the energy system.

2.4.2 Challenges and the Role of PtX in Denmark

The Danish PtX business has concerns regarding enough affordable and available electricity from RES in the future. A survey conducted by Rambøll highlights that out of the 50 most important PtX stakeholders in Denmark, 67% think the biggest barrier and challenge for PtX is the electricity price and availability. In the survey, it is also highlighted that one of the most important prerequisites for PtX to succeed and scale up is that the state helps secure enough electricity. A challenge for the development of PtX in Denmark is, that the timelines for electricity generation and hydrogen infrastructure do not align. Several challenges appear because of this, as the developers of renewable electricity do not necessarily want to commit to investment in wind and solar farms if there are uncertainties and no guarantees for offtakes of the electricity. The PtX business in Denmark wants to produce and export hydrogen as well as other PtX fuels like methanol and sustainable aviation fuels (SAF), but this opposes the Danish Government's strategy on carbon capture and storage [64], as this strategy neglects the use of CO_2 combined with hydrogen to produce methanol and focuses on storage of CO_2 in the underground instead. The right circumstances from a political side are lacking, which creates uncertainties on investing in PtX projects in Denmark and opportunities in the USA and other countries in the EU are therefore explored. The PtX industry and business in Denmark clearly state that the politicians in Denmark, but also the EU, are responsible for the improvement of the framework conditions. [65]

The IEA has made key recommendations to scale up hydrogen production and one of these recommendations states that hydrogen should play a role in long-term energy strategies, where national planning and goals should include hydrogen [66]. Examples of countries which focus on hydrogen on a political and strategic level are Sweden [67], Germany [68], Scotland [69], Canada [70], South Africa [71], and Denmark [61].

The Danish Energy Agency and the Government state that PtX is essential if Denmark is to meet the national climate goals [61].

The PtX strategy presented by The Danish Government [61] focusses on:

- The contribution from PtX to fulfil the national climate goals.
- The regulatory framework and infrastructure must be in place if the strength position of Denmark is to be utilized and PtX can act on market terms.
- The interaction between the energy system and PtX should be strengthened.
- Denmark must export PtX technologies and products.

Denmark is a country with several strength positions when it comes to PtX. Denmark has several companies throughout the entire value chain of PtX, a high knowledge level and a good research environment regarding RE, and has excellent wind resources both onshore and offshore, access to biogenic CO_2 and a solid energy system. The biggest expenses to the production of hydrogen are the price of electricity, electricity tariffs and the investment in the electrolyser where the expenses contribute 1/3 each. To lower the price of hydrogen production in some cases, the PtX project can have a direct line meaning no connection to the national grid and thereby no tariffs. [61]

Several studies have been conducted on the role of hydrogen and PtX in the future Danish energy system. One of these studies is conducted by the before mentioned IDA. The role PtX plays in this study is to fuel sectors that cannot be directly electrified. The study highlights, that one of the challenges concerning PtX is the high new electricity demand, where flexibility on the consumption side is crucial. [35]

Another study by Kountouris et al [17] investigates the optimal operation of a Danish energy hub, where PtX plays an important role. This study highlights the importance of a proper market environment, which at the moment is highly uncertain, and a lack of clear policy support despite political ambitions. The need for additional support is important if investments in PtX projects are to happen to incentivize the production of fuels from PtX. Market conditions such as price and regulation should be improved for a successful PtX development environment. [17]

Another study focusing on the Danish electricity market and scale-up effects of grid-connected PtX projects is Panah et al [72], where they identify taxes, the price of electricity and levies as barriers if the hydrogen price is to match fossil fuels-based alternatives. A solution to these barriers can be to subsidize electricity and/or carbon taxes. This study also highlights that electricity prices and CAPEX are the dominant barriers to hydrogen cost reduction.

Besides technical studies, a stakeholder analysis focusing on conflict topics has also been conducted by Andreasen & Sovacool [73], where 21 of the most influential actors within the hydrogen industry in Denmark are included. This study highlights that even within the hydrogen industry stakeholders do not agree on crucial aspects, such as decentralized or centralized hydrogen infrastructure, and whether hydrogen should be subsidized or not. A crucial conflict among the hydrogen stakeholders in Denmark is the “chicken and egg” problem and whether the industry should develop first, or consumers should buy hydrogen-dependent technologies. Even though there are discrepancies between the stakeholders, they highlight that the hydrogen infrastructure is lacking in Denmark and the existing customers of hydrogen are willing to pay an additional price for the hydrogen as it is generally more expensive than the alternatives. [73]

Studies on the role and potential role of biomass and biogas in combination with PtX have also been conducted such as Mortensen et al [74], Bube et al [75], Rinaldi et al [76], and Nielsen & Skov [77] as methanol is to play an important role in the future energy system, and it can be produced by using the biogenic CO_2 from e.g. biogas plants [25]. This report does however not focus on the available biogenic CO_2 from biogas and its future role, but the importance of this is nevertheless acknowledged.

Neither of the above-mentioned studies includes exporting PtX fuels to other countries, but they highlight certain challenges regarding PtX.

Based on current research and analyses the biggest challenges concerning PtX are:

- Enough affordable and available electricity from RES in the future.
- The consumer must be somehow flexible in most cases.
- Uncertain market conditions and regulations must be improved.
- Lack of political financial support schemes.
- High operational costs when connected to the grid due to high taxes, electricity prices and levies.
- Lack of hydrogen infrastructure
- The “chicken and egg” problem – who should make the first large-scale move?

Peer review studies on the hydrogen export potential of Denmark have to the best of our knowledge not been conducted even though Denmark has excellent export opportunities. Based on the current literature and the knowledge gap regarding the lack of reports and detailed analysis on the Danish potential export of hydrogen this report investigates how Denmark can be an exporter of hydrogen and if it is feasible, along with identifying potential challenges and means of actions within the PtX business. This aligns with the fact that the Danish PtX industry and the Danish Government's PtX strategy both want to focus on exporting hydrogen.

2.5 Summary and Problem Specification

This chapter highlights the need for PtX to decarbonize the global energy system in sectors that cannot be directly electrified, while also highlighting the challenges PtX faces. EU regulations set the criteria for producing renewable hydrogen and how to secure renewable electricity to produce hydrogen. To secure the production of renewable hydrogen through renewable electricity the criteria of additionality, temporal and geographical must be maintained to comply with RFNBO.
Several predictions on RES capacities in 2030 and 2045 have been made, alongside political goals

for the development. These predictions and goals do not align, which makes it difficult to be certain about the future RES capacity. The Danish Government has, however, made a PtX strategy for Denmark setting out targets for PtX capacity towards 2030 and general regulatory goals, but not much action has been taken based on the strategy. Studies elaborate on the need for additional support from the Danish government if investments in PtX projects are to be made. The support can come in terms of financial support, better-marked conditions and improved regulatory conditions.
Besides the lack of political action, PtX stakeholders highlight that the biggest barriers for the PtX industry are the price of electricity, availability of electricity and timelines of RES and electrolysers that do not align.

PtX is not only relevant in Denmark and Denmark has good prerequisites to be an exporter of PtX fuels, as there are excellent RE resources, a high security of supply, good competencies throughout the entire value chain of PtX and a well-connected power grid to other countries, but to achieve the international position of an exporter of PtX fuels the right amount of renewable electricity needs to be available, and the regulatory framework needs to be implemented. Several studies elaborate on the hydrogen export potential of several countries around the world, but no detailed studies on the Danish hydrogen export potential have been concluded. This does not align with the visions of the Danish PtX industry and the Danish Government's PtX strategy, which both mention the focus on export in the future.

3 Research Question and Research Design

As found in *Chapter 2* PtX plays a crucial role in the future energy system to reach the national and global climate goals. Several goals have been made for RE, including PtX, which indicates a political interest in the business. Most of the current regulation is, however, only at an EU level, which is why it is appropriate to investigate potential challenges and means of action which relevant stakeholders within the Danish PtX industry find.

As Denmark is a relatively small country with excellent wind resources, it is relevant to investigate if it is feasible for Denmark to export hydrogen, to help accommodate other countries' climate goals. The analyses of this report focus geographically on Denmark and take its point of departure to reach the climate goals before 2045. As previous studies, to the best of our knowledge, have not yet been conducted regarding the economic feasibility of Denmark exporting hydrogen combined with a regulatory analysis, the report aims to answer the following research question:

3.1 Research Question

What are the socio-economic consequences of Denmark being an exporter of hydrogen, and how can the existing regulatory framework be improved to accommodate the development of PtX towards 2045?

The following sub-questions aim to answer the research question.

Sub-questions

1. How can different configurations of scenarios be modelled to accommodate a hydrogen export demand?
2. What are the socio-economic results of Denmark being an exporter of hydrogen through scenarios with different hydrogen export capacities?
3. Which regulatory challenges and means of action do stakeholders within the PtX value chain identify in the Danish PtX business?

3.2 Delimitation

The report focuses on the total capacities and generation of the electrolyser and RES and does not focus on the exact location of new wind turbines and electrolysers. The report thereby delimits from exact energy infrastructure costs as these are dependent on the exact proximity to the electrolyser. It is acknowledged that these costs can impact both the business- and socio-economic and the LCOH. To include a cost for the energy infrastructure, an overall analysis is made based on the announced hydrogen PtX projects. By doing this an average proximity to the infrastructure can be found and the costs are therefore included in the economic calculations, even though they might differ from specific projects, as the exact location is known.

The AEC electrolyser is chosen as the type of electrolyser in the scenarios as this is the most mature and commercial type of electrolyser and an analysis and discussion on the other two types of electrolysers, PEM and SOEC, are therefore not included in the report.

The waste products of the PtX process, like oxygen and excess heat, are also excluded from the scope of this report and are not examined further. The excess heat can potentially strengthen the business case and socio-economy if it is sold and used in the district heating grid. If the excess heat from the PtX process replaces other fuels, these types of fuels will decrease. The oxygen can potentially be used at hospitals or in chemical reactions. Just as the analysis of the use of waste products from the PtX process is not included, it is furthermore not analysed, what and where exactly the hydrogen should be used.

A final delimitation is the analysis and inclusion of the water demand for the electrolyser. It is assumed enough high-quality water is available and the costs of buying and potentially treating the water are not included.

3.3 Research Design

Following *Figure 5* presents the research design of the analysis of this report. The research design is divided into three columns, the first *Research outline* includes the research question and corresponding sub-questions, the second column *Chapters* includes the chapters of the analysis, the discussion and the conclusion, and the final column *Theory and methods* presents in which part of the analysis the different methods and theories are utilized. Lines between the *Research outline* and *Chapters* columns indicate in which chapters of the analysis the different sub-questions are answered. In addition, the lines between the *Chapters* and *Theory and methods* columns show which theories and methods are used to answer the sub-question in each of the chapters of the analysis. The theories are marked in the green colour, while the methods are marked in the orange colour. The SES theory is in the research design connected to the research question, this is because the SES theory sets the frame of the entire analysis and report and is not used specifically in a chapter but is used throughout the report.

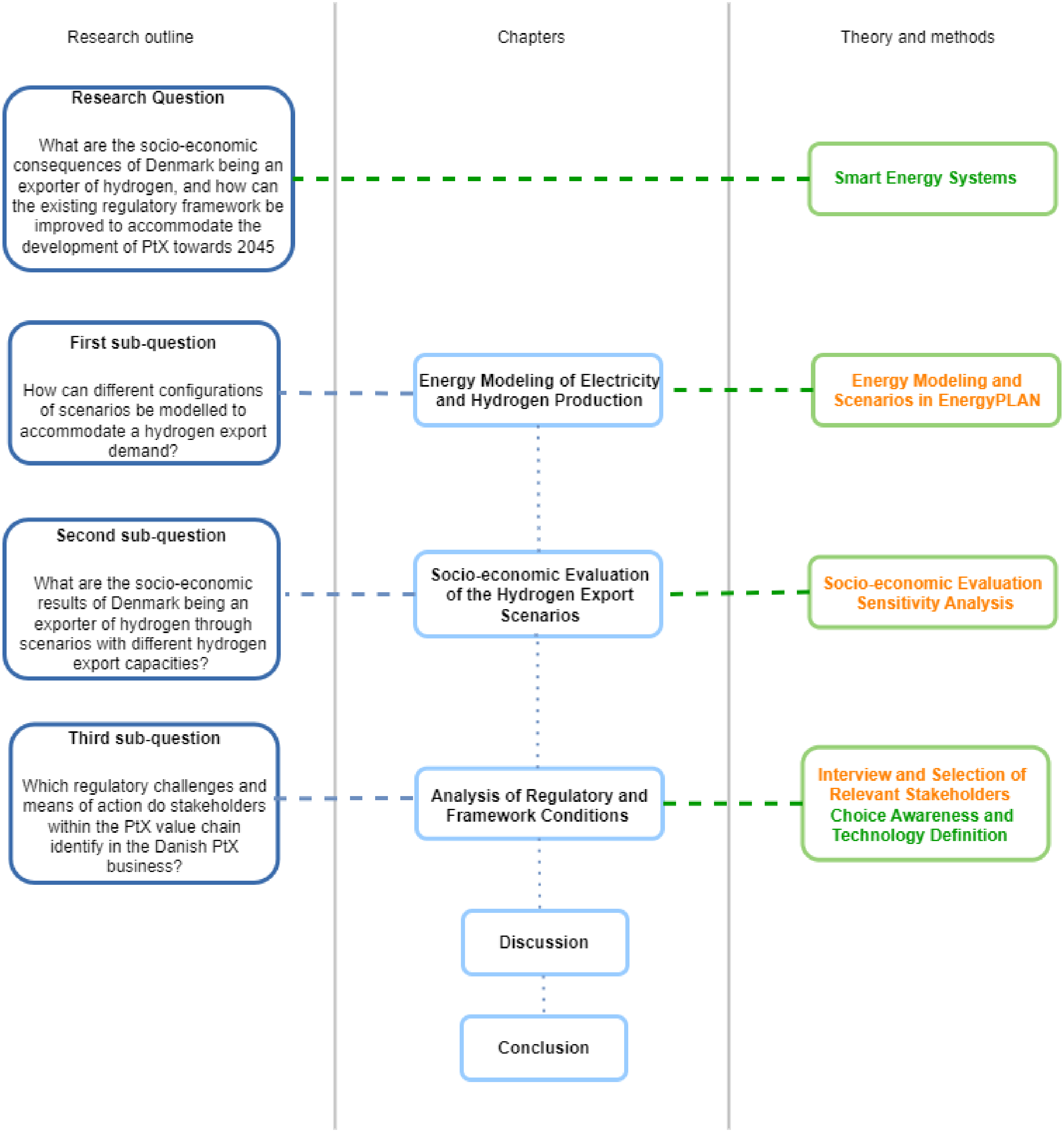


Figure 5: Research Design.

4 Theoretical Framework

This chapter introduces the applied theories in the report. The theories set the framework for the analysis and how the research question is answered. The theories of SES and choice awareness are introduced. SES is used to define the rational understanding of the future energy system and how this should be planned. Choice awareness and the technology definition are utilized to determine how PtX is a radical technology change, which is presented within the choice awareness theory, and how it can be implemented in the Danish energy system.

4.1 Smart Energy Systems

Several new definitions have appeared during the last years when it comes to energy systems and infrastructure. These describe new paradigms in the design of future energy systems. One of the concepts that has appeared is SES. The main concept of the SES theory is the holistic approach and inclusion of the entire energy system. As electricity production, e.g., is becoming more fluctuating due to the increase in electricity produced from RES, effective and low-cost solutions can be found if this sector is combined with other sectors such as the heating, gas, and transportation sectors. This is a general point as the most efficient and low-cost solutions are found if the sectors are combined instead of being planned individually. [5]

It is first and foremost important to analyse the energy system in the context in which the overall energy system is to be operated and investigate which resources are relevant to include and what the political context is. When combining several sectors, it is important to keep in mind that these sectors influence each other, and it is important to consider if the most feasible solution is identified. Synergies appear when having a coherent approach to the energy system, such as having heat and gas storage instead of electricity storage, as it is possible to use electricity for heating and hydrogenation purposes. [5]

This report bases the energy system on the SES concept and perceives the energy system as a whole with the integration of different sectors instead of “silo planning”, where the sectors are planned individually. The SES concept is used as the foundation of the understanding of the future energy system and in the modelling of different export scenarios. PtX naturally complies with the SES concept, as the electricity sector is combined with other sectors depending on the X product. If the PtX project is grid-connected, it can help stabilise the national electricity grid in times of high production. It is, however, important, as mentioned in *section 2.2*, that, the electrolyser does not run entirely on excess electricity but also has a baseload as it is too inefficient and expensive if the electrolyser is only operating for a few hours. So even though it might benefit the electricity grid, the business case still has to be favourable for the developer of the PtX project, which is why the entire energy system has to be the perspective. [5]

4.2 Choice Awareness

The main aspect of the choice awareness theory is the implementation of radical technological changes, which could be from fossil fuels to RES, and how this can be implemented on a societal level [78]. The theory concerns the collective perception and societal level and emphasizes that society does have a choice to make better decisions for the future. Choice awareness is knowing that society is not automatically presented with a true choice, being aware that there is always a choice, and finally being aware of how to ensure a true choice. The choice concerns collective decision-making, and it involves several different individuals and organisations which have different interests and perspectives and might be at different levels of power. The choice awareness theory differs between a true choice and a false choice. A true choice is where the choice stands between two or more real options. While the false choice scenarios are represented by a situation where there is no choice, only one choice is presented, or the choice is presented as an illusion and is, therefore, not a real option. [78]

As a part of the democratic decision-making structure, the choice awareness theory advocates for including different technical alternatives, feasibility studies, and public regulatory measures. The theory concerns that existing organisational structures will affect political decision-making by eliminating choices. The theory enlightens that different organisations have their agendas and interests, which is why existing organisations might keep or even eliminate RE projects from the agenda and political decision-making process. [78]

The choice of PtX comes into play by raising awareness and information on the subject to the public, but the collective perception can be manipulated if organisations convince society that the alternative is not possible if it, e.g., cannot comply with technical requirements, saying it is too expensive or the fluctuating RES makes it impossible to apply to the energy system. The Danish Government has conducted a PtX strategy for Denmark and highlights the importance of PtX to reach the climate goals, but this could be argued to be a representation of having “no choice” as either PtX is implemented in the energy system or we cannot meet the climate goals. [78]

PtX is, however, not perceived as an entirely clear “no choice” as it often is mentioned as an addition to electrifying the society, where electrification should be the priority and thereafter PtX products should be used in sectors that are difficult to electrify [13]. The concept of PtX also covers several technologies so hydrogen is e.g. not the only choice, but other end-products are also possible, and several choices appear [26]. An alternative to expanding PtX can be to focus on the demand side and how to decrease this, but this choice is not the focus of the Danish climate goals as the expansion of the energy system and its components are the focus along with the export of different energy carriers [61]. The choice of exporting PtX products can also be discussed as different advantages and disadvantages appear when this is the focus. It can be discussed if the PtX products should be produced in the countries with the best conditions, which can be an advantage, or if each country should meet their own demands [49]. If PtX is not considered as a choice the alternatives would cause other problems, as the energy system either will not meet the climate goals if it continues using fossil fuels, or the bioenergy resources would be used to a degree, which is not sustainable [79]. Choice Awareness theory argues that public participation, and thus the awareness of choices, has been an important factor in successful decision-making processes, which is why the inclusion of the public is also an important aspect of successfully developing a PtX project [5].

4.2.1 Technology Definition and Radical Technology Change

Technology is defined based on Hvelplund & Djørup [80] as *technique, organisation, knowledge, profit and product,* also known as the technology dimensions. There has been a transition, and there still is, in the technologies used in the energy system based on fossil fuels, to an energy system based on RES. The new technologies needed in the future energy system should be able to harvest and transform fluctuating sources into energy, at the right time and amounts. [80]

The definition of technology is also used by Lund [78] to define and describe radical technological change. If one of the technology dimensions is changed, at least one of the others will follow.

Depending on the number of dimensions that are changed the more radical the change is. For the change to be radical, at least two dimensions must be affected. The transition from a fossil fuel-based system to RE systems is considered a radical technological change. It is important to examine the technological change in an institutional and historical context, as existing institutions might favour established technologies. A wind turbine might e.g. change the profit and knowledge, but the product itself is not changed if it is compared to a coal-fired power station, as they both produce electricity.

When applying the technology definition to PtX, the *technique* is the electrolyser technology and the internal components. It has not been developed on a large scale in Denmark before, but only on small-scale, test facilities. Several large-scale projects are, however, announced and are in progress [81]. When having this change in the technique, the other four dimensions are also changed, when it comes to PtX. New types of *organisations* must appear when implementing PtX. On the organisational level, it is also important to know the political and economic aspects, to understand who oversees the legislation, and how this supports PtX. As new organisations appear, they do not necessarily have the same capital for inventing in RE and PtX, as existing organisations. New *knowledge* is also needed both on the technological side regarding the capacities and scaling up of PtX, and on the financial and societal side to understand how to develop the best business case while also planning for the entire energy system as in the SES theory. The *profit* dimension is also changed as new developers, organisations, investors, and owners are involved in PtX projects. Lastly, the *product* itself is also changed when focusing and developing PtX. The product is the entire PtX components and value chain, along with the final PtX fuels. The technology definition and the different components can be seen in *Figure 6.*

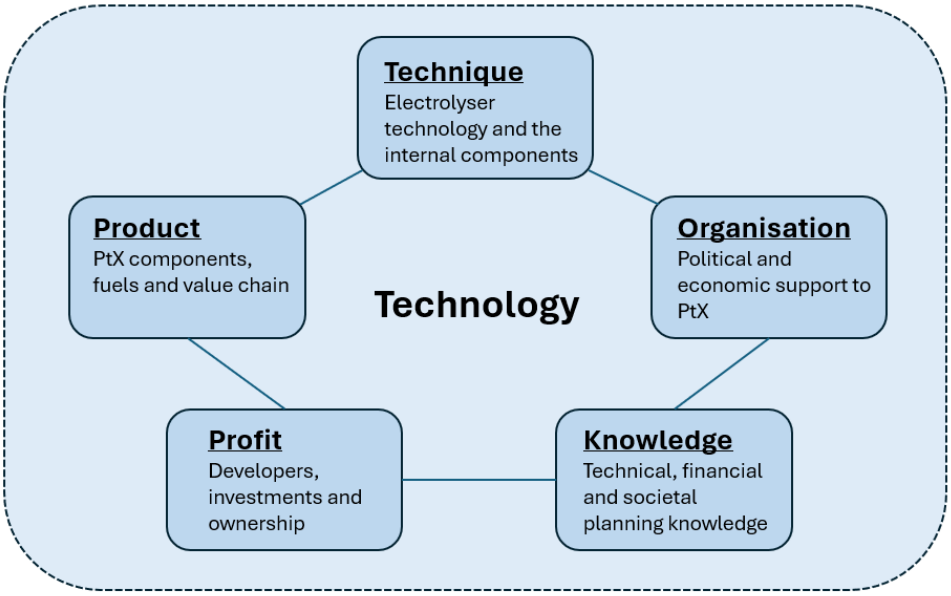


Figure 6: Technology definition and the five components.

The technology change requires potential new planning and implementation frameworks, which is why the societal level is important to investigate to understand how the technological change can be planned for most favourably. The five technology dimensions are applied to investigate the changes PtX has on the energy system and society. Understanding the five dimensions helps to understand who should be involved in the planning, who is affected by the change and how to plan for the change.

When it comes to PtX, the change in the technique affects all of the other dimensions and PtX is thereby considered a radical technological change. Thus, in the report, the different dimensions are used to process the results of the conducted interviews to ensure a holistic planning process. By doing so it becomes more clear which barriers and challenges appear in the different dimensions, and how these can be handled is analysed further.

In the work with radical technological change and PtX, it is assumed in this report that the choice of PtX in Denmark has been made to help reach the climate goals. This is due to the fact, that official policies and goals include PtX, several planned PtX projects are in the pipeline, and studies on the Danish energy system include PtX in the future [35], [36], [61]. A PtX project can be designed in different ways both regarding the exact technologies and how the projects should interact and connect with the energy system. The different choices that must be made for a PtX project are also affected by regulations and policies. Different scenarios are developed for export potentials in Denmark to underline the importance of choices.

5 Methodology

This chapter presents the methodology of the report. Each method contributes to answering the research question and ensures a comprehensive analysis. The applied methods in the analysis are socio-economic calculations, including sensitivity analysis, energy modelling in EnergyPLAN and interviews with relevant stakeholders within the PtX business in Denmark. The interview is an example of a qualitative method, while the other methods are quantitative. The mix of both qualitative and quantitative methods ensures to cover different data points that aim at answering the research question in the best possible way.

5.1 Socio-economic Evaluation

The socio-economic evaluation shows the economic consequences the society will face from a scenario and its alternative scenarios. During the socio-economic analysis, it is essential to evaluate the pros and cons of the project, also known as a socio-economic cost-benefit analysis where the result of the analysis will be an economic assessment. The socio-economic standpoint is that the investments of the project are viewed as one joint investment, even though it might be several individual actors investing. [82]

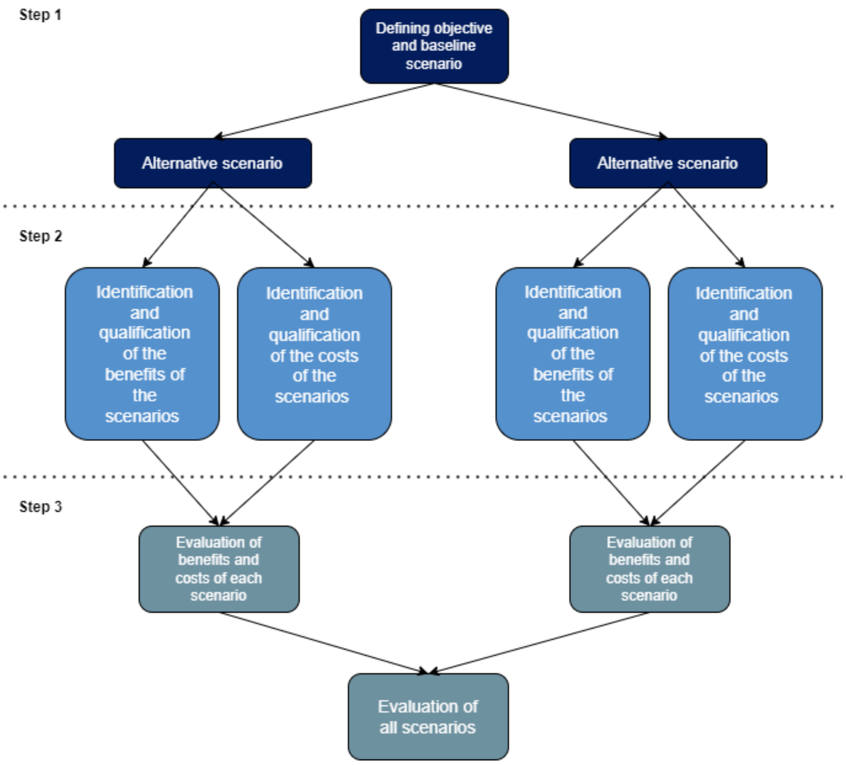


Figure 7: Steps of the socio-economic evaluation [83].

The Danish Ministry of Finance [83] recommends that the socio-economic evaluation is split into three steps, as shown in *Figure 7.* The first step identifies the baseline scenario, and alternative scenarios to the baseline scenario and defines the purpose and objectives of the evaluation. The second step includes the identification and qualification of the benefits and costs of the scenarios, this also includes the calculation of the net present value (NPV) of each scenario. In the last and third step, the evaluation of the scenarios takes place. The pros and cons of each scenario are evaluated and compared to each other. [83]

The mentioned three steps of the socio-economic evaluation are used to structure the analysis of the report. The first step is included in *Chapter 6*, where the baseline scenario is presented alongside the configurations of the alternative scenarios. Thereafter, both the second and third step is included in *Chapter 7* where the NPV of the scenarios are calculated, alongside an evaluation of the scenarios through a sensitivity analysis of relevant parameters.

In the second step, the result of the analysis is assessed as the NPV, which is calculated based on the investments of the project (cost) and the revenue of the project (benefit) in the lifetime of the project. The NPV is the total sum of future cash flows in the value of the current time. If the NPV value is positive then the project investigated is socio-economically feasible, as the investment of the project will be paid back during the lifetime of the project. [83]

The NPV formula can be presented as follows in *Equation 1*: [82], [83]

$$NPV_{t=0} = \sum_{t=1}^{T} \frac{B_t - C_t}{(1+n)^t}$$

Equation 1: Net Present Value.

The factors in the formula are presented as follows [82], [83]:

- B_t represents the revenue and cost of the project in every year of the lifetime.
- C_t is the investments of the project in year 0.
- n is the discount rate.
- t is the lifetime of the project.

The calculation of the NPV will further in this report be used in a sensitivity analysis.

5.1.1 Net Present Value Economic Parameters

This section describes the economic parameters that are included in the NPV calculations. A table of the investment parameters of included technologies is presented in *Appendix 12.1,* while the revenue, investments, and yearly costs of the scenarios are found in *Appendix 12.2*.

The socio-economic calculations of this report follow the Socio-economic Guidance Document from the Danish Ministry of Finance but do not follow it meticulously [82]. The analysis in this report does not include the value of emissions, as the prediction is that all energy production in the year 2045 will be from renewable sources.

Several of the technologies included in the economic calculations have a longer lifetime than the 30 years which is chosen for the analysis. This means that a scrap value of the investment of the technologies is included in the calculations. It is important when calculating the NPV to only include the investments that are relevant to the lifetime of the project. For technologies which have a longer lifetime than the project, an annual investment cost is calculated to show the investment cost of the technology in every year of its lifetime, and then only include the annual investment cost in years that correspond with the lifetime of the project. [82]

The capacities of the included technologies in this analysis, are based on the additional capacities of the technologies in the different scenarios compared to the capacities of the baseline scenario. This also includes the balance of natural gas and the import/export of electricity.

Economic values

The NPV calculations for the scenarios are based on a 30-year lifetime as this is the lowest lifetime of the technologies. The 30 years lifetime is the lifetime of the offshore wind turbines, while other technologies have longer lifetimes of 32, 40, 50 or even 100 years [84]. The decision to use the lowest lifetime of 30 years is made to ensure all technologies are operational within the lifetime with just the initial investment and do not need reinvestments. Furthermore, the scrap values of the technologies with a lifetime longer than 30 years are calculated, to accommodate the difference in the lifetimes and to only include the investments in technologies within the 30-year lifetime of the calculations [82].

The value of the discount rate for the NPV calculations is 3.5% set by the Danish Ministry of Finance for investments between 0 and 35 years [85].

The net tax factor is included in the calculation of the NPV at a value of 28% set by the Danish Ministry of Finance [85]. The net tax factor represents the tax, charge and subsidies that are added to the investments, O&M, and costs of electricity and fuel for a given project in the socio-economic analysis [82].

Electrolyser and hydrogen storage

Investment costs for an AEC electrolyser of 100 MW are used to calculate the NPV in the three scenarios. The electrolyser has a lifetime of 32 years, which is longer than the 30-year lifetime used in the calculations. This means that the scrap value is calculated for the electrolyser, to only include the investments made within the project lifetime of 30 years. The annual investment cost of the electrolyser in scenario 1 is 154 MEUR, 233 MEUR in scenario 2 and 312 MEUR in scenario 3. The annual investment cost is then used to calculate the total investment of the electrolyser in the different scenarios.

The hydrogen storage technology that has been chosen for the three scenarios is the underground storage of hydrogen. This is based on the technology the baseline scenario from the IDA's Climate Response 2045 report predicts to be used in the year 2050 [86]. The already-used natural gas storage in salt caverns can be converted to contain hydrogen instead [87], just as natural gas pipes can be repurposed for hydrogen pipes based on expected technological advances [88]. This underground storage is also useful when dealing with fluctuating electricity production from RES such as PV and wind turbines as it can be utilised for grid balancing large capacities. The capacity of the hydrogen storage in the different scenarios is decided through the EnergyPLAN analysis. In the baseline scenario for the IDA's Climate Response 2045 report, the hydrogen storage capacity is set to contain four days of hydrogen production using the total electrolyser capacity. The same equivalence is used to calculate the optimal hydrogen storage capacity for scenarios 1 through 3. The lifetime of the hydrogen storage is 100 years, which means that for this technology the scrap value is also calculated.

The price of green hydrogen offtake is decided based on the report from Capgemini et. Al. [89] who through surveys with the industry have predicted a hydrogen price. They predict that the price of hydrogen will by 2030 be below 7 EUR/kg, and 21% of those who surveyed predict the price to be between 3-4 EUR/kg. In the NPV calculations of this report, the hydrogen price that is used is therefore decided to be 3 EUR/kg. [89]

Electricity and gas infrastructure, and electricity price

The NPV also includes the investment in electricity distribution lines connecting the PtX projects to the national electricity transmission grid. The electricity distribution lines are predicted to be placed in newly developed areas, and the cable line is predicted to be a single line of 100-500 kW [90]. The expansion of the existing electricity transmission grid is not included in the analysis.

The investment in hydrogen pipelines is also included in the NPV calculations. It is expected that the hydrogen pipelines in this analysis will connect the PtX projects to the national hydrogen network. It is further assumed, that the national hydrogen pipeline from the European Hydrogen Backbone report [49] is established before 2045, so only additional pipelines from the European hydrogen backbone pipeline to the hydrogen PtX projects are included in the analysis. It is furthermore assumed, that the national hydrogen pipeline can handle the produced hydrogen. The hydrogen pipes are at 140 bar and 250-500 MW [90]. The electricity distribution lines have a lifetime of 40 years, and the hydrogen pipelines have a lifetime of 50 years, which means that the scrap value is calculated for both technologies.

The electricity price used in the socio-economic calculations is from the 2023 Analytical Prerequisite document for Energinet conducted by the Danish Energy Agency. The electricity price chosen is an hourly prediction of the spot price of the year 2040 and is used to calculate the price of imported and exported electricity in all three scenarios at hourly values. [91] It is acknowledged that the forecast of electricity prices is very uncertain and that these might change in the future, which might influence the result of the NPV analysis.

Offshore wind turbines

The NPV calculations also include the investment costs of additional offshore wind turbine capacity. The lifetime of the offshore wind turbines is 30 years. For the offshore wind turbines, the total nominal investment is used to calculate the investment cost included in the socio-economic analysis. The nominal investment for the offshore wind turbines includes the installation of the turbines, project development, array cables, foundation structure, grid connection and the investment in the turbines. [84]

Fuel balances

When adding more wind capacity to the system other fuel balances might be affected. To accommodate this change, a fuel price is added to the NPV calculations, as some of the fuels might increase or decrease. The only fuel balance that changes in the scenarios is the natural gas consumption. The natural gas is assumed to be imported, and an import price of natural gas in 2045 is used at 7.5 EUR/GJ [92].

Operation and maintenance

The socio-economic calculations also include the operation and maintenance prices (O&M) for the included technologies. This includes the calculation of O&M for the electrolyser capacity, offshore wind turbines, hydrogen storage, electricity distribution and hydrogen pipelines. Including the O&M costs is consistent with the Socio-economic Guidance Document from the Danish Energy Agency [82].

5.1.2 Sensitivity Analysis

Several of the included economic parameters in the socio-economic calculations are very uncertain as they are predictions of the future [82]. This includes, among others, the electricity price, the price of hydrogen, and the investment costs. Sensitivity analyses will therefore be conducted to test the robustness of the socio-economic evaluations against smaller or bigger changes in economic parameters. The purpose of the sensitivity analysis is to determine if the socio-economy of the scenarios is sensitive to changes, and the projects therefore are risky to invest in, and at what cost the NPV is positive and the project thereby is economically feasible [82].

The methodology of the sensitivity analysis is to vary the economic parameters in question with percentage intervals of 10%.[82]. In this analysis, the electricity price, the price of hydrogen, and the investment cost of offshore wind turbines will vary with the appropriate percentage to reach a positive NPV for all scenarios.

5.2 Energy Modelling and Scenarios in EnergyPLAN

To model the different scenarios the tool EnergyPLAN is used as it aligns with the definition of SES, since it can do hour-by-hour analysis and includes the different sectors and the interaction between them [5]. EnergyPLAN is also used as it simulates the operation of the national energy system, which is the purpose of this report. The model is developed and maintained by Aalborg University and includes the electricity, heating, cooling, industry, and transport sectors. [93]
EnergyPLAN is a techno-economic input/output energy system model and aims to analyse different scenarios of energy systems. EnergyPLAN also analyses operations and can both simulate an energy system and optimize it. The purpose of the model is to analyse the consequences of implementing different technologies and investments, and it is used for regional or national planning. Amongst several other technologies, the model includes electrolyser and hydrogenation. EnergyPLAN is used to design different scenarios for the export of hydrogen, while also considering the entire energy system, which aligns with the choice awareness theory on describing different alternatives. [94]

These scenarios are designed based on choice awareness which means they should comply with the following criteria [94], [95]:

- The scenarios are designed in a way that makes them comparable in the central parameters such as the electrolyser and RES capacities and production.
- Radical technological changes should be able to be included in the analysis.
- Suitable information for a feasibility study should be included.
- Understandable results should be provided and a consistent methodology.

5.2.1 Composition of Scenarios in EnergyPLAN

The scenarios of this report are made based on the EnergyPLAN model that was developed for the IDA's Climate Response 2045 report. The baseline scenario will therefore be the EnergyPLAN model for the IDA's Climate Response 2045 report, and the following scenarios will both be compared to the baseline scenario and each other. [35]

The RES capacities for the baseline scenario are visualised in below *Table 3.*

Year	Wave power	PV	Onshore wind	Offshore wind	PtX
2045 IDA predictions	0.132 GW	10 GW	5 GW	14 GW	4.8 GW

Table 3: Share of RES in the IDA's Climate Response 2045 document [35].

The baseline EnergyPLAN model from the IDA's Climate Response 2045, models the entire energy system of Denmark including electricity, heat, industry, and transport. The following scenarios of this report will therefore also include the entire energy system of Denmark, but the only parameters of focus are the offshore wind capacity, PtX capacity, hydrogen export, hydrogen storage, import/export of electricity, Critical Excess Electricity Production (CEEP), and transmission line capacity to surrounding countries.

The analysis of this report will be split into three scenarios differentiating on the capacity of the electrolyser. The electrolyser capacity of scenario 1 will be increased by 5 GW compared to IDA Climate Response 2045, in scenario 2 the electrolyser capacity will be increased by 10 GW, and with 15 GW in scenario 3. The purpose of increasing the electrolyser capacity is to enable the possibility of including a hydrogen export capacity in the system, and to do so there must be available electrolyser capacity in the system. The hydrogen demand for transportation in the system will not be changed from the baseline scenario, but the total demand for hydrogen will increase as a hydrogen export demand is added.

It has been decided to only increase the capacity of the offshore wind turbines, which means that the capacity for wave power, PV, and onshore wind turbines for the following three scenarios will be the same as in the baseline scenario. Several energy analysis studies in Denmark concluded that the greatest potential for expanding the RES production capacity is through offshore wind turbines [96], [97], [98]. The reason why investments in offshore wind turbines are included in the analysis is to comply with RFNBO, as one of the criteria is the condition of only receiving renewable electricity from an electricity-producing unit that is no more than 36 months old from the COD of the RFNBO-producing unit [20]. Furthermore, the expansion of PtX is expected to follow the expansion of offshore wind turbines [41] and the electricity for PtX will mainly be provided by the offshore wind turbines [43], which is why the focus is solely on offshore wind turbines in the analysis.

The transmission line capacities between Denmark and adjacent countries have been updated in the three scenarios compared to the baseline scenario, as more connections have been introduced since the baseline scenario was made [84]. The updated capacity is the capacity in 2024 and is 8,880 MW and is both for import and export. As shown in the below Table 4, Denmark has transmission lines to Norway, Sweden, The Netherlands, the UK, and Germany. EnergyPLAN does not differentiate between import and export, hence the lowest value is chosen. [99], [100]

Transmission line capacity to surrounding countries			
Norway from Jutland	1,700	MW	
Sweden from Jutland	680	MW	680 MW is the export capacity. The import capacity is 740 MW.
The Netherlands from Jutland	700	MW	
Germany from Jutland	2,500	MW	
UK from Jutland	1,400	MW	[100]
Sweden from Zealand	1,300	MW	1,700 MW export capacity, and 1,300 MW import capacity
Germany from Zealand	600	MW	
Total	8,880	MW	

Table 4: Transmission line capacity of Denmark to surrounding countries [99].

A relevant parameter that has been updated in the three scenarios compared to the baseline scenario is the efficiency of the electrolyser. The chosen electrolyser technology is AEC with an efficiency of 71.5 % in the year 2040 [27]. The year 2040 is selected for the electrolyser efficiency as the electrolyser units are expected to be built before the year 2045 and to be in operation in the year 2045. The capacity of the hydrogen storage is also updated in the three scenarios to accommodate the new electrolyser capacity and hydrogen export demand.

If there is an additional export of electricity to the system it is shown as CEEP, which also shows that the system is not efficient at incorporating the RES production.

In EnergyPLAN there are two ways of modelling the production of hydrogen export. The first way is to include a fixed baseload production of the electrolyser, while the other way is to let the production of hydrogen export follow the CEEP from the included offshore wind turbine production. This means that instead of exporting the excess electricity production, it is utilised to produce hydrogen. There is also a third option of combining the two and therefore having the model run on both a fixed hydrogen export production and a production that follows CEEP. In this third option, the production that follows CEEP will only produce in hours where there is CEEP in the system and there is available capacity in the electrolyser. If the production of hydrogen export only follows the CEEP there would be hours where the electrolyser would not operate. On the contrary, if the hydrogen export production only follows a fixed production profile, there would be hours when the system must import electricity for the electrolyser to run, and there is no guarantee that the imported electricity is renewable. EnergyPLAN will first fulfil the fixed hydrogen demand that is set from the baseline scenario and hereafter produce hydrogen for export based on CEEP. [101]

Important values in the EnergyPLAN output are the electricity export, the electricity import, CEEP, export of hydrogen and electrolyser capacity. To find a common denominator throughout the scenarios and to be able to compare the scenarios amongst each other and decide on an RES capacity, it is chosen to keep the CEEP value as close to the CEEP value in the baseline scenario, which is 4.9 TWh/year.

5.3 Interview and Selection of Relevant Stakeholders

To get a better overview and understanding of the regulatory and challenging aspects of PtX projects and processes, interviews with different stakeholders are conducted as a method of research to identify barriers and potential needed regulatory and political changes. As multiple stakeholders are included in the PtX value chain, the most important and relevant to hydrogen PtX projects are analysed concerning their power over a hydrogen PtX project and their willingness to influence a hydrogen PtX project in a positive direction. Before analysing the stakeholders, the PtX value chain is shown in *Figure 8* to highlight which stakeholders to include in the identification. It is acknowledged that other stakeholders can influence the PtX project if the end product is not hydrogen.

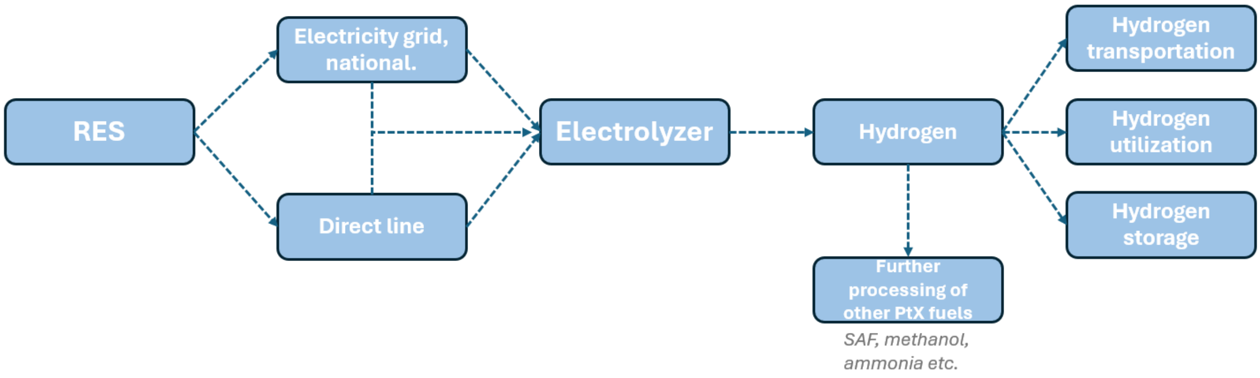


Figure 8: Overview of the PtX value chain.

As this report only focuses on hydrogen, the "Further processing of other PtX fuels" box is not described in more detail, as the technologies and value chain are dependent on the end product. Within the PtX value chain, different stakeholders appear. They might have their own goals and agenda, but they are all important for the development of a PtX project, as several components are included. The stakeholders within the "RES" box do not necessarily have a goal of producing hydrogen through PtX, as their product is electricity produced from RES, and their business case might be just as good or even better if they sell the electricity to the national grid. The development of PtX can however be favourable for the "RES" stakeholders, as a large electricity demand appears, and their product thereby becomes even more essential. The knowledge of the stakeholders in the different categories is important for a successful PtX project, as the different stakeholders have their expert knowledge within the different categories of the value chain. The value chain in *Figure 8* concerns the technical side of a PtX project so developers, non-governmental organisations (NGOs), public authorities etc. are not included in the figure, but these are important stakeholders and are included in the stakeholder identification analysis. The different stakeholders are identified based on the PtX value chain, brainstorming and general literature review on PtX projects. The main stakeholders included in the development and planning of a PtX project based on these three things are analysed regarding their power over a hydrogen project and their willingness to influence a hydrogen project in a positive direction.

The identified stakeholders and their willingness and power relation to a hydrogen PtX project can be seen in *Figure 9*. Whether the stakeholders are directly included in a PtX project or not can also be seen.

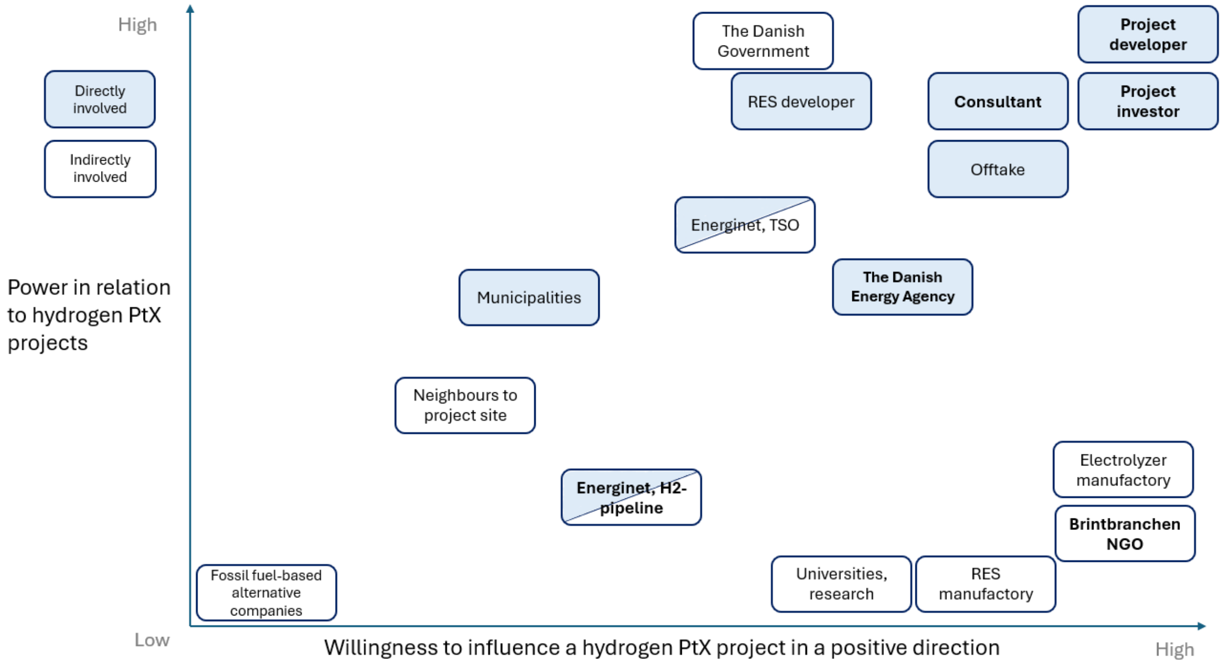


Figure 9: Stakeholder analysis of power over a PtX project and willingness to influence a PtX project.

The stakeholders marked in bold in *Figure 9* are interviewed, due to their different levels of power and willingness to influence a PtX project, and due to differences in direct or indirect involvement in a PtX project.

Several of the stakeholders can be placed in various places in the figure, as their willingness to influence the projects positively can be influenced by different factors. The neighbours to a PtX project might e.g. be more positive towards a PtX project if they can benefit from the project. If, on the other hand, the local citizens are concerned about noise, smell, safety etc., they will probably be less willing to influence the project in a positive direction and even influence it in a negative direction. Some of the stakeholders have a more indirect influence on the project such as the RES manufactory. If wind turbine manufacturers for any reason cannot or do not produce wind turbines, it can influence the PtX project, if a wind project cannot be developed and the electricity should therefore be acquired elsewhere. It is however in this analysis of the stakeholders assumed, that RES are available, and they are therefore at the low end of the power axis. Another example of where the context is important is the TSO. If the PtX project is connected with direct lines, they do not have as big of an influence. If the project on the other hand is grid-connected, the TSO can play a major role.

The stakeholders who are interviewed are described below along with the interview approach and the purpose of the interview:

- **Infrastructure developer, Energinet**: Energinet is a company under the Danish Ministry of Climate, Energy and Supply, that owns and develops the Danish transmission- and gas grid, and is responsible for the security of supply [102]. Energinet also has a central role in establishing and developing the future Danish hydrogen infrastructure, so the production of hydrogen has a favourable interaction with the existing energy system [103]. Two interviews were conducted with Energinet. The first interview was with Tine Lindgren, a chief engineer in their hydrogen development department, on the 29th of April 2024 and the second interview was with Sofie Holmbjerg, a development consultant in their hydrogen development department, on the 30th of April 2024. The interviews aimed to get a better understanding of the planning of the future energy infrastructure and potential challenges in the planning process, when considering PtX.

- **NGO, Brintbranchen:** Brintbranchen is a lobbying organisation, that works with stakeholders within hydrogen and PtX in Denmark. They represent the entire value chain within the PtX industry, where a strong network of stakeholders is represented, and have dialogues with decision-makers, and authorities, to ensure the Danish hydrogen business is heard [104].
  Political and international manager Mette Kirstine Schmidt and regulatory and analytical manager Adriana Guerenabarrena were interviewed on the 8th of May 2024 through Microsoft Teams. The interview aimed to understand the regulatory and political constraints of an NGO.
- **Consultant, COWI:** COWI is a consulting engineering company that works within several fields like engineering, architecture, energy, and environment. COWI works, amongst others, with PtX, wind energy, PV, carbon capture utilization and storage, electrifying, and sector coupling.[105]
  Technical director for green fuels and energy in COWI Denmark Jeppe Grue was interviewed on the 30th of April 2024 at the COWI Aalborg office. The interview aimed to understand the PtX planning process through a consulting company's perspective, and which challenges, if any, they face during the general planning of a PtX project.
- **Project developer, European Energy:** European Energy develops, invests, and builds renewable energy projects and works within the entire value chain of PtX [106]. Project developer Søren Hartz was interviewed on the 8th of May 2024 through Microsoft Teams. The interview aimed to understand the PtX planning process through a project developer's perspective, and which challenges, if any, they face during the general planning of a PtX project.
- **Actual PtX project and project investor – HØST/Copenhagen Infrastructure Partners**: HØST PtX Esbjerg is a large-scale hydrogen and potential ammonia PtX project located in Esbjerg, Denmark, where the development of the project began in 2021. The project is managed by Copenhagen Infrastructure Partners (CIP) and is expected to be 1 GW. The produced hydrogen will be transported to the German market through hydrogen pipelines [107].
  The project director David Dupont-Mouritzen was interviewed on the 23rd of April 2024 through Microsoft Teams. The interview aimed to get a better understanding of the concrete planning process for an actual PtX project in Denmark and understand the challenges they have faced during the process, if any. Furthermore, it was possible to get insights from a project investor's point of view, as David Dupont-Mouritzen works for CIP.
  After the interview was held it was published that CIP only focuses on hydrogen from the HØST project and does not focus on ammonia until the proper market is in place [108]. After the interview, it was furthermore published that CIP has entered a hydrogen partnership with German Uniper so they in 2028 will offtake the hydrogen through hydrogen pipelines in Denmark and Germany [109].
- **The Danish Energy Agency, PtX secretariat**: The PtX secretariat within the Danish Energy Agency is responsible for inquiries regarding PtX and regulation. The main tasks of the PtX secretariat are to assist stakeholders with guidance on permits and approval procedures related to PtX and to support the development of PtX in Denmark. [25]
  Michael Hougaard Sandgreen who is a special advisor in the PtX secretariat was interviewed on the 23rd of April 2024 through Microsoft Trams. The interview aimed to get a better

understanding of the expansion of PtX from a national authority along with the challenges they face in the planning and working with PtX.

The conducted interviews are all semi-structured meaning that the questions are planned in advance along with the sequence for asking them. If follow-up questions or additional questions appeared during the interview, they were asked to get the best possible flow in the interviews. [110] An interview guide was sent before the interview, so the interviewee had a chance to plan some of the answers and know the topics of the interviews. When conducting and processing the interviews it is important to keep in mind, that the interviewee, to some extent, can present personal opinions instead of the opinion of the company or organisation. To avoid this in the best possible manner the interview guide was followed.

All the interviews were recorded, with acceptance from the interviewees, to process the interview afterwards. Notes were taken during the interview, but to make sure no important statements were left out, the recordings were heard after the interviews. All the relevant statements from the interviews can be found in *Appendix 12.4*. Here a matrix is created for all the interviews as some of the questions are the same, and by having the matrix it is more manageable to compare the statements with each other and find the relevant statements. The notes and statements included in the matrix are the relevant ones from the interview meaning, if topics appeared with no relevance to the scope and topic of the report it is not included in the matrix. The most important statements are marked in bold, so it is more manageable to navigate in the matrix.

The different statements from the interviews will be analysed by the technology definition described in *Section 4.2.1*. This means the statements will be processed based on whether they fit in the technique, organisation, knowledge, profit or product category of the technology definition. By doing so, it becomes more clear what type of regulation and planning is needed, and within which category the biggest challenges appear.

6 Energy Modelling of Electricity and Hydrogen Production

This chapter analyses how different configurations of scenarios can be modelled to accommodate a hydrogen export demand, as presented in sub-question one. The chapter initially analyses the balance between CEEP and a fixed hydrogen export demand, whereafter the three scenarios are created and analysed. When the scenarios are conducted, they are compared to each other and the baseline scenario. The space requirements of the offshore wind turbines and the number of wind turbines are also analysed to get an understanding of the needed space.

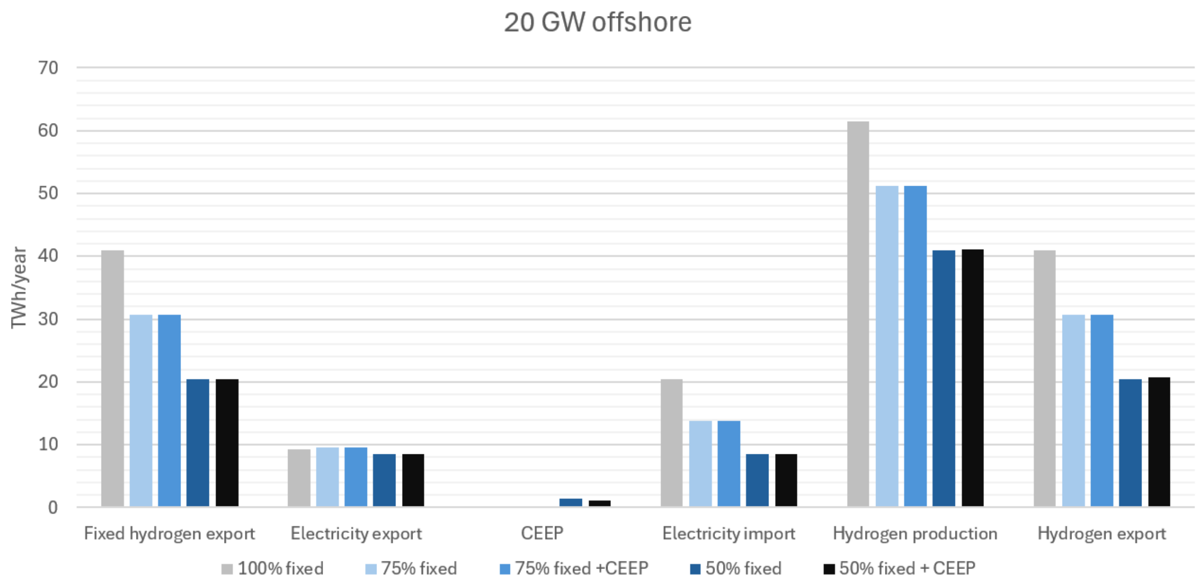
Three scenarios in EnergyPLAN have been modelled to investigate the appropriate offshore wind capacity for the capacity of the electrolyser and hydrogen export. In all three scenarios, the same capacity for PV and onshore wind have been used, respectively 10 GW and 5 GW, which is the same as in the IDA's Climate Response 2045 report. This means that the only RES capacity output from the scenarios is the capacity of the offshore wind turbines.

The main problems and challenges regarding energy systems based entirely on RES are, that the amount of available biomass is limited compared to fossil fuel alternatives, and solar and wind have fluctuating production patterns. This is why it is important to include some kind of storage or conversion technologies when designing 100% RE systems, where smart grid infrastructure also is an important aspect. [94]
It is important to highlight, that EnergyPLAN is optimising the operation of the energy system and do not optimize the investments, but these are just a result of the analysis [94]. The financial output of EnergyPLAN is, however, not used in the analysis of the NPV, but other financial data is used. When designing the scenarios they are all based on an energy system based on 100% RE, so fossil fuel alternatives are not analysed, as this does not comply with the climate goals, even though cheaper or more flexible energy systems might appear if some types of fossil fuels also are included. The scenarios in this report are designed to optimize the energy system, where financial, export and demand aspects are analysed.

The first analysis analyses the relation between a fixed hydrogen export production and the impact CEEP has on the hydrogen production. When the relation between a fixed hydrogen export and CEEP is known, three different scenarios are analysed where the analysis aims to identify an offshore wind capacity.

6.1 Operation of Electrolysers

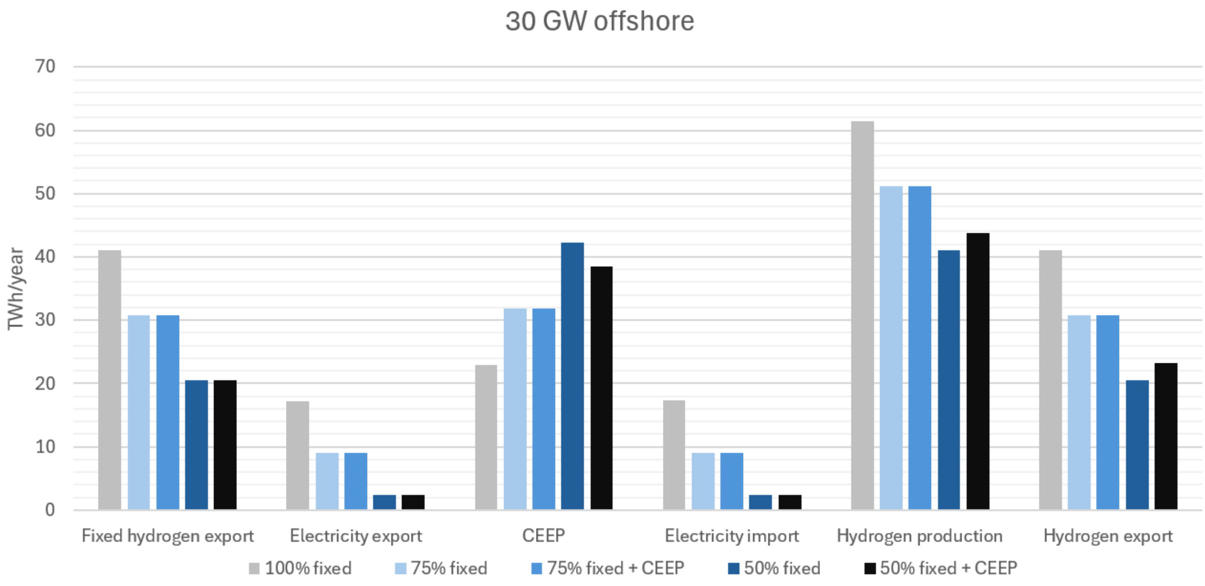
To conduct the analysis and design the different scenarios, the first step is to analyse the configuration between a fixed hydrogen export and what difference the addition of a hydrogen production that follows the CEEP in the system does. When analysing the relation between the fixed hydrogen export and CEEP, the balance between CEEP, electricity export, electricity import, hydrogen export and the capacity factor of the electrolyser is in this analysis considered. To analyse the relation between the fixed hydrogen export and CEEP, two fixed offshore capacities are chosen to showcase the impact on different fixed hydrogen exports and whether it is with or without CEEP, and an electrolyser capacity of 9.8 GW is used. The offshore wind capacities chosen for the analysis are 20 GW and 30 GW and the analysis of the electrolyser operation can be found in *Appendix 12.6*. For the different offshore wind capacities, energy systems have been modelled in EnergyPLAN with a 100% fixed hydrogen export, 75% fixed hydrogen export with and without CEEP, and 50% fixed hydrogen export with and without CEEP. Graph 2 and Graph 3 show the results of the 20 GW offshore wind capacity analysis and the 30 GW offshore wind capacity analysis.



Graph 2: Fixed hydrogen export and CEEP analysis with 20 GW.

	Capacity factor
100% fixed	100%
75% fixed	83%
75% fixed + CEEP	83%
50% fixed	67%
50% fixed + CEEP	67%

Table 5: The capacity factor of the electrolyser with 20 GW.



Graph 3: Fixed hydrogen export and CEEP analysis with 30 GW.

	Capacity factor
100% fixed	100%
75% fixed	83%
75% fixed + CEEP	83%
50% fixed	67%
50% fixed + CEEP	71%

Table 6: The capacity factor of the electrolyser with 20 GW

When the electrolyser is operational based on a 100% fixed hydrogen export value, CEEP is the lowest as the electricity is not exported, but used by the electrolyser, as the hydrogen export is the highest, when the electrolyser is based on a 100% fixed hydrogen export. The capacity factor is also the highest when the electrolyser is based on a 100% fixed hydrogen export value as seen in *Table 5* and *Table 6*. The electricity import is however high when the electrolyser is based on a 100% fixed hydrogen export value, which makes the system dependent on large shares of imported electricity. This creates several challenges as it is not known, how the electricity, that is imported, is produced. The year for the analysis is 2040 so it is assumed, that most of the European electricity system is based on RES, but other issues might appear such as, when the wind production is low in Denmark it can also be low in other countries, and the electricity is thereby produced by sources like hydropower or bioenergy.

If the electrolyser is based on a 50% fixed value both with and without CEEP, CEEP is the highest as the hydrogen production is relatively low, and the electricity is therefore exported. The hydrogen export is also the lowest when the electrolyser is based on a 50% hydrogen export value. Before CEEP has an actual effect on the hydrogen production, the electrolyser should be based on a 50% fixed hydrogen export value, which means, that the addition of CEEP to the 75% fixed hydrogen export system does not change the production or import/export.

In the further analysis, a 75% fixed hydrogen export value with CEEP is chosen. This is based on making the energy system more accurate than with the 100% fixed value, where the system is very dependent on imported electricity, nor using the 50% fixed + CEEP value, where CEEP, the capacity factor of the electrolyser, and the hydrogen export is low.

Even though the addition of CEEP to the 75% fixed value with 20 GW and 30 GW does not change the production of hydrogen, this might change, when making the scenarios, which is why the addition of CEEP is chosen. The 75% fixed hydrogen export energy system has an acceptable capacity factor for the electrolyser, a decent import of electricity and CEEP, combined with a decent hydrogen export compared to the configurations between CEEP and fixed hydrogen export. The capacity factor of the electrolysers at 83% aligns with the capacity factor of the HØST project, which is predicted to be around 80% [111]. The capacity factor further aligns with the expected capacity factor of European Energy's PtX project of 75% in Kassø [112].

6.2 Scenarios

As found in *Section 6.1* the scenarios are based on a 75% fixed hydrogen export production and CEEP. When this relation is known, the offshore wind capacity can be found. The scenario analysis aims to find an offshore wind capacity where CEEP is on the same level as in the baseline scenario which is 4.9 TWh/year to be able to compare the scenarios amongst each other.

For the three scenarios, an increase in electrolyser capacity and hydrogen storage capacity is included in the EnergyPLAN model. Following *Table 7* gives an overview of the capacity of the electrolysers and the respective hydrogen storage capacities.

Scenarios	Increase in electrolyser capacity (on top of 4.8 GW)	Hydrogen storage capacity
Scenario 1	5 GW	705 GWh
Scenario 2	10 GW	1.065 GWh
Scenario 3	15 GW	1.426 GWh

Table 7: Overview of electrolyser capacity and hydrogen storage capacity of the scenarios.

The hydrogen storage is used in the EnergyPLAN models for the scenarios and the socio-economic calculations. As mentioned in *Section 5.1.1* the calculation of the size of the hydrogen storage follows the method applied in the IDA's Climate Response 2045.

6.2.1 **Baseline Scenario – IDA's Climate Response 2045**

As mentioned in *section 5.2.1* the IDA's Climate Response 2045 EnergyPLAN model is the baseline scenario, as it is assumed, that all demands in Denmark are covered in this model, and it is thereby possible to investigate export scenarios of hydrogen as the IDA EnergyPLAN model does not include any hydrogen export. The result of the IDA EnergyPLAN model can be seen in *Table 8*.

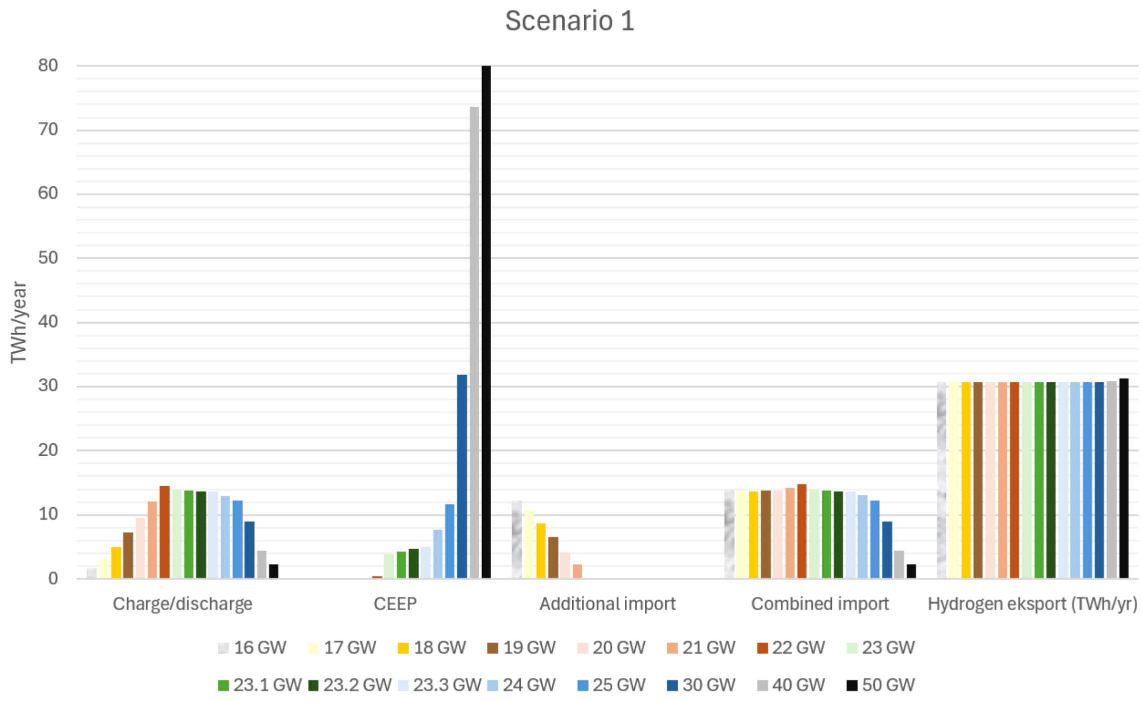
IDA EnergyPLAN baseline scenario	
Offshore wind capacity	14 GW
Hydrogen export	0 TWh/year
Electricity export	4.9 TWh/year
CEEP	4.9 TWh/year
Electricity import	4.9 TWh/year
Hydrogen production	20.49 TWh/year
Capacity factor	68%

Table 8: Result of the IDA EnergyPLAN model.

The numbers stated above are used in the later comparison of the scenarios and the IDA EnergyPLAN model.

6.2.2 Scenario 1

The scenarios aim to investigate the influence the offshore wind capacity has on the energy system and hydrogen export. The analysis of the different scenarios can be found in *Appendix 12.7*. When choosing the offshore wind capacity for scenario 1 a balance between the factors in *Graph 4* is considered along with a CEEP value on the same level as in the IDA EnergyPLAN model.

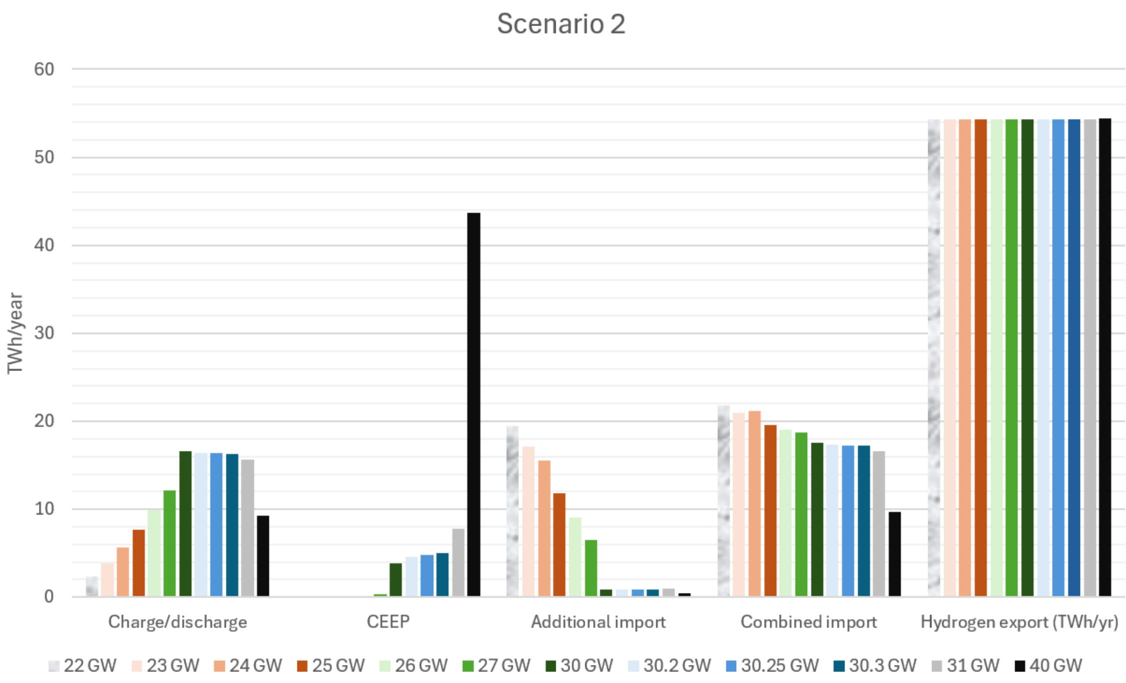


Graph 4: Overview of the result from the analysis for scenario 1 based on different offshore wind capacities.

The fixed hydrogen export value is 30.75 TWh/year in scenario 1, as this corresponds to 75% of the maximum capacity of the electrolyser. At all the offshore wind capacities the electrolyser has a capacity factor of 83.5% except the ones with an offshore capacity of 40 and 50 GW, but here the capacity factor of the electrolyser only increases to 83.6% and 84.4%. The hydrogen export is the same at all offshore wind capacities at 30.75 TWh/year except for the offshore wind capacities of 40 GW and 50 GW. At these two offshore wind capacities, the hydrogen export is respectively 30.8 TWh/year and 31.34 TWh/year. These results show that CEEP is not included in the hydrogen production before an offshore wind capacity of 40 GW is used, and at this capacity, it is relatively limited how much more hydrogen is produced compared to the other offshore capacities. When comparing the relatively limited increase in the hydrogen export, when the offshore wind capacity increases, and the investment cost of wind turbines, it is not immediately relevant to increase the offshore wind capacity to 40 GW. The CEEP value, furthermore, increases significantly at an offshore wind capacity of 40 GW and 50 GW. The offshore wind capacity where CEEP is on the same level as IDA's EnergyPLAN model, is at 23.3 GW. The offshore wind capacity for scenario 1 is therefore 23.3 GW, an increase of 9.3 GW compared to the baseline scenario.

6.2.3 Scenario 2

When choosing the offshore wind capacity for scenario 2 a balance between the factors in Graph 5 are considered along with a CEEP value on the same level as in the IDA EnergyPLAN model.

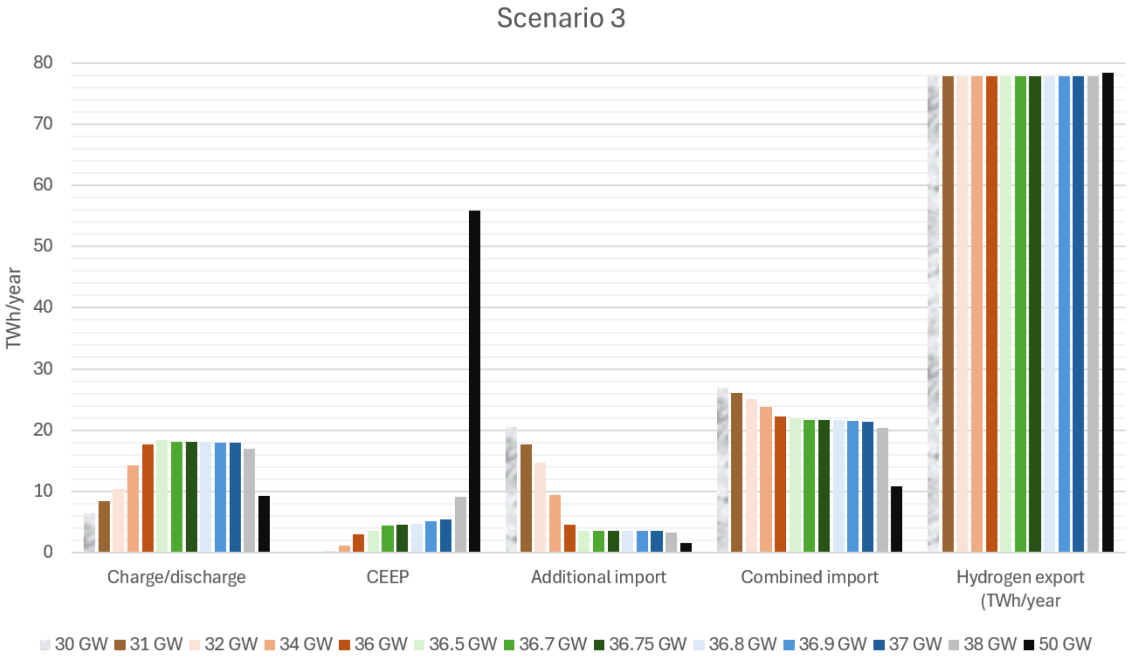


Graph 5: Overview of the result from the analysis for scenario 2 based on different offshore wind capacities.

The fixed hydrogen export value is 54.3 TWh/year in scenario 2, as this corresponds to 75% of the maximum capacity of the electrolyser. At all the offshore wind capacities the electrolyser has a capacity factor of 80.7% except the one with an offshore capacity of 40 GW, but here the capacity factor of the electrolyser only increases to 80.8%. The hydrogen export is the same at all offshore wind capacities at 54.3 TWh/year except for the offshore wind capacity of 40 GW. At this offshore wind capacity, the hydrogen export is 54.4 TWh/year. These results show that CEEP is not included in the hydrogen production before an offshore wind capacity of 40 GW is used, and at this capacity, it is limited how much more hydrogen is produced compared to the other offshore capacities. The CEEP value, furthermore, increases significantly at an offshore wind capacity of 40 GW. When comparing the limited increase in the hydrogen export, when the offshore wind capacity increases, and the investment cost of wind turbines, it is not immediately relevant to increase the offshore wind capacity to 40 GW. The offshore wind capacity where CEEP is on the same level as the IDA EnergyPLAN model, is at 30.3 GW. The offshore wind capacity for scenario 2 is therefore 30.3 GW, an increase of 16.3 GW compared to the baseline scenario.

6.2.4 Scenario 3

When choosing the offshore wind capacity for scenario 3 a balance between the factors in *Graph 6* are considered along with a CEEP value on the same level as in the IDA EnergyPLAN model.

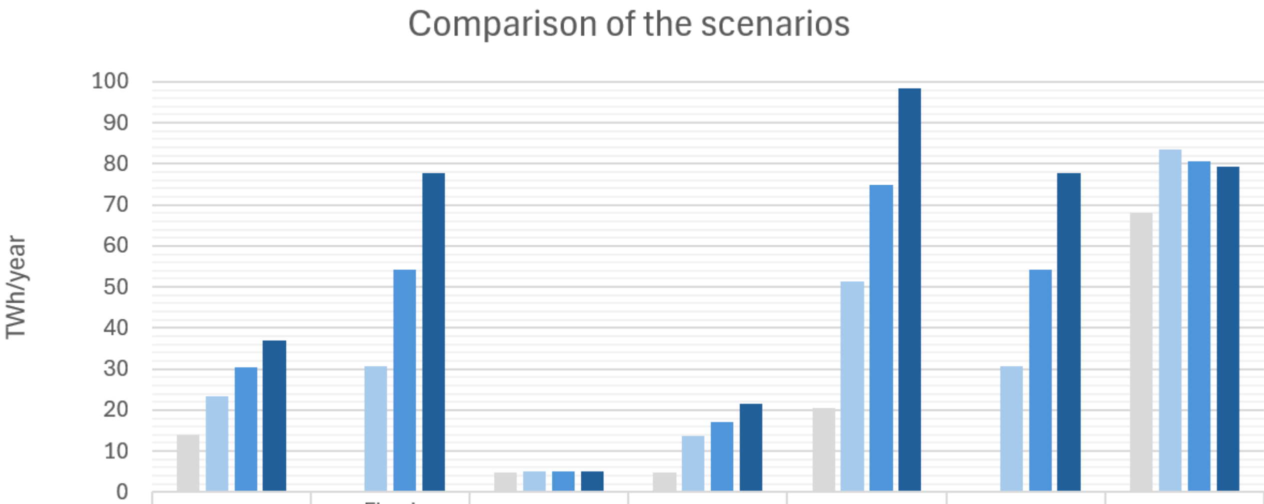


Graph 6: Overview of the result from the analysis for scenario 3 based on different offshore wind capacities.

The fixed hydrogen export value is 77.85 TWh/year in scenario 3, as this corresponds to 75% of the maximum capacity of the electrolyser. At all the offshore wind capacities the electrolyser has a capacity factor of 79.3% except the one with an offshore capacity of 50 GW, but here the capacity factor of the electrolyser only increases to 79.8 %. The hydrogen export is the same at all offshore wind capacities at 77.85 TWh/year except for when the offshore wind capacity reaches 50 GW. At this offshore wind capacity, the hydrogen export is 78.44 TWh/year. These results show that CEEP is not included in the hydrogen production before an offshore wind capacity of 50 GW, and at this capacity, it is limited how much more hydrogen is produced compared to the other offshore wind capacities. When comparing the limited increase in the hydrogen export, when the offshore wind capacity increases, and the investment cost of wind turbines, it is not immediately relevant to increase the offshore wind capacity to 50 GW. The CEEP value, furthermore, increases significantly at an offshore wind capacity of 50 GW. The offshore wind capacity where CEEP is on the same level as the IDA EnergyPLAN model, is at 36.9 GW. The offshore wind capacity for scenario 3 is therefore 36.9 GW, an increase of 22.9 GW compared to the baseline scenario.

6.2.5 Comparison of the Scenarios

The electrolyser capacity for scenarios 1, 2, and 3 is respectively 9.8 GW, 14.8 GW and 19.8 GW, whereas the electrolyser capacity in the IDA's Climate Response 2045 report is 4.8 GW. The result of the EnergyPLAN analysis can be seen in Graph 7 and is based on Appendix 12.5.



	Offshore wind capacity (GW)	Fixed hydrogen export	CEEP	Electricity import	Hydrogen production	Hydrogen export	Capacity factor (%)
IDA	14	0	4.9	4.9	20.49	0	68.2
Scenario 1	23.3	30.75	5.04	13.62	51.24	30.75	83.5
Scenario 2	30.3	54.3	5.04	17.21	74.79	54.3	80.7
Scenario 3	36.9	77.85	5.09	21.51	98.34	77.85	79.3

Graph 7: Overview of the three scenarios and the IDA Climate Response 2045.

Compared to the IDA EnergyPLAN model all the scenarios have a higher capacity factor for the electrolyser. Naturally the hydrogen production and export are also higher for the three scenarios than the baseline scenario, as it does not include the export of hydrogen. When the scenarios are compared it is also showcased, that the higher the offshore wind capacity, the higher the export of electricity. The higher electricity export can be explained by the wind turbines producing more electricity than needed for the electrolyser in some hours, and the higher the wind capacity the higher the production of electricity. Even though the electrolyser is getting larger in each scenario and thereby needs more electricity, there are still hours with overproduction of electricity. The electricity import also increases with the offshore wind capacity, but it is still low in all the scenarios. The import of electricity happens in hours of no production of electricity from the offshore turbines or not sufficient production of electricity.

According to the Danish Energy Agency, the capacity of an offshore wind turbine in 2040 will be 25 MW [84]. This means an additional 372, 652 and 916 offshore wind turbines will be added to the Danish energy system compared to IDA's Climate Response 2045 for scenarios 1, 2, and 3. If the hydrogen export in the scenarios is compared to the predicted German hydrogen demand in 2045 on 350 TWh [113], the scenarios can contribute with respectively 9%, 16% and 22% of this demand. The predicted German hydrogen demand in 2045 is not only imported hydrogen but also national-produced hydrogen, so the scenarios can contribute to a fairly high share of the hydrogen. In 2030 Germany wants to import 30-90 TWh of hydrogen in comparison [114] but it is however expected to increase in 2045.

The space requirement for an offshore wind turbine in 2040 is 0.17 km^2/MW [84]. This corresponds to space requirements for scenarios 1, 2, and 3 on 1.580 km^2, 2.768 km^2, and 6.267 km^2 additional space compared to IDA's Climate Response 2045. The space requirements for the offshore wind turbines can be seen in *Figure 10*.

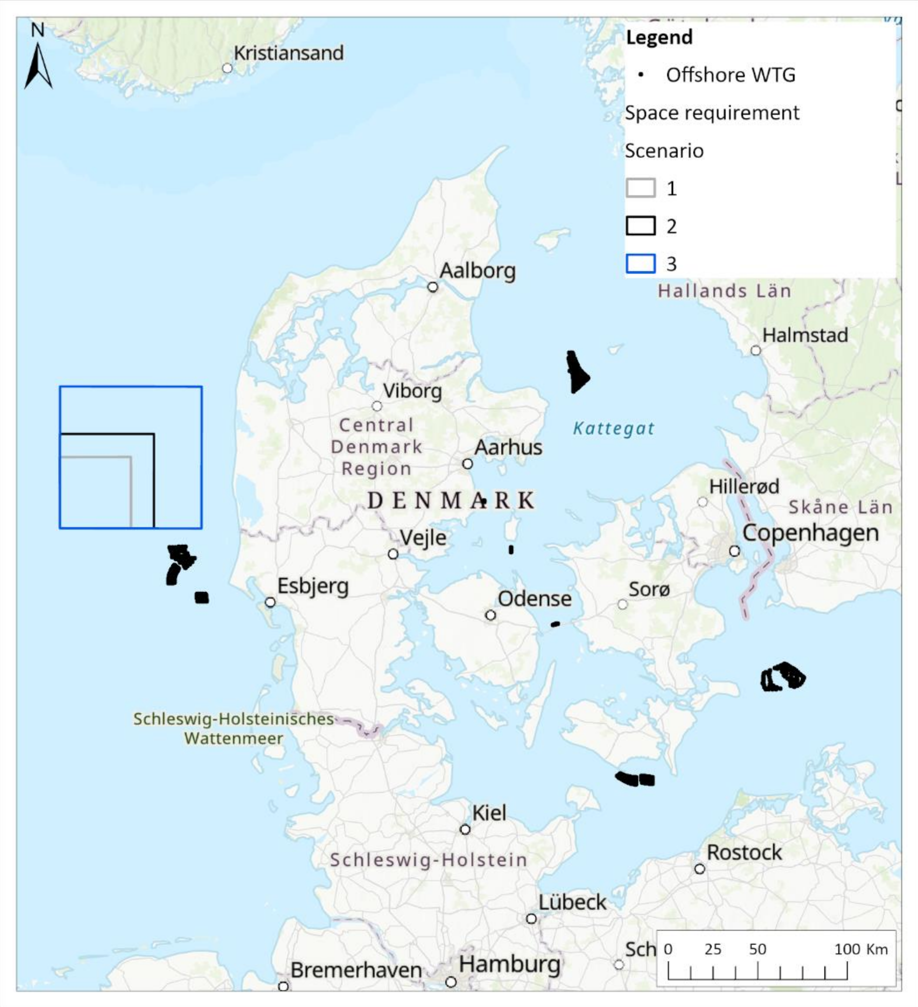


Figure 10: Space requirement for the different scenarios.

The areas for the offshore turbines are mapped as one single area for the different scenarios, but the areas will most likely be distributed throughout different projects and areas. The offshore wind turbines constitute a large share if it is compared to the land area of Denmark. Scenario 1 corresponds to 3.7% of the total Danish land area, scenario 2 corresponds to 6.5% and scenario 3 corresponds to 14.6%. The additional space requirement compared to IDA's Climate Response 2045, and the additional offshore wind turbine capacity compared to IDA's Climate Response 2045 can be seen in Table 9.

	Additional space requirement compared to IDA (km^2)	Additional offshore wind turbine capacity compared to IDA (GW)
Scenario 1	1,580	9,3
Scenario 2	2,768	16.3
Scenario 3	6,267	22.9

Table 9: Additional space requirement for the three scenarios compared to IDA's Climate Response 2045.

The space requirements and offshore wind turbine capacity constitute a large share, but hydrogen export can help decarbonize especially Germany. Even though it is positive, that Denmark theoretically can export large amounts of hydrogen, it also must be socio-economic beneficial for Denmark and a good business case for the developers and investors before PtX projects are realized.

6.3 Preliminary Summary

The configuration between a fixed hydrogen export and CEEP is analysed to be 75% fixed hydrogen export + CEEP. This configuration is chosen as it is more realistic than having a 100% fixed hydrogen export or 50% fixed hydrogen export due to the amount of imported electricity, the CEEP value, the capacity factor of the electrolyser and the hydrogen export. The offshore wind capacity of the three different scenarios is found through EnergyPLAN analyses to be respectively 23.3 GW, 30.3 GW, and 36.9 GW. At these capacities, the CEEP value is on the same level as the baseline scenario. When the offshore wind capacity increases with the scenarios all values increase except the capacity factors which decrease. This means the electricity export, electricity import, and hydrogen export increase from scenarios 1 to 3. The offshore wind capacities require a lot of space and require respectively 1.580 km^2, 2.768 $km^{2,}$ and 6.267 km^2 for scenarios 1, 2, and 3, but on the other hand, the scenarios constitute respectively 9%, 16% and 22% of the German hydrogen demand.

7 Socio-economic Evaluation of the Hydrogen Export Scenarios

The following chapter will analyse the socio-economic results of Denmark exporting hydrogen with different hydrogen export capacities, as presented in the second sub-question. The inputs for the socio-economic calculations are based on the infrastructure costs of the additional offshore wind turbine capacity compared to the baseline scenario that occurs when adding a hydrogen export demand, the inclusion of new PtX capacity to accommodate the new hydrogen demand, and the following spatial analysis of hydrogen and electrical infrastructure.

7.1 Spatial Analysis of Announced Hydrogen Projects and their Proximity to Infrastructure

To include hydrogen pipeline and transmission lines costs in the economic calculations an average distance to the infrastructure must be identified. As these costs are dependent on the exact location and the proximity of the RES, infrastructure, and electrolyser, it is not possible to include the exact numbers in this report, as the exact location is not within the scope of the analysis. It is acknowledged that these costs are very case-dependent for the specific PtX project, and they can influence the projects to be more favourable or less favourable than if the average costs are included and can affect the LCOH.

To find an average distance to the hydrogen pipeline and transmission line, announced hydrogen PtX projects in Denmark are mapped in Geographic Information Systems (GIS) including operational, planned and expansion projects. GIS is a spatial system, where it is possible to map, create, analyse and manage different types of data, where the geographic context can be understood and analysed [115]. The energy islands are not included in the analysis as the distance only is relevant onshore in this analysis. Only projects of a minimum of 50 MW are chosen in the analysis.

The included layers in the GIS analysis are:

- Transmission lines [99], [116]
- Proposed hydrogen pipeline [49]
- Announced hydrogen PtX projects with a minimum capacity of 50 MW [81]

The location of the hydrogen projects is based on research and the project name, as only a few of the projects have an exact location announced. A total of 23 announced hydrogen projects are at least 50 MW in Denmark and are used to find the average distance to the transmission lines and the proposed hydrogen pipeline [81]. The proposed hydrogen pipeline is based on the European Hydrogen Backbone report, and the report states it is assumed the pipelines will be built before 2030 [48]. The layers used in the analysis can be seen in *Figure 11* including the location of the transmission lines, proposed hydrogen pipeline and announced hydrogen PtX projects with a minimum capacity of 50 MW.

Figure 11: Proposed hydrogen pipeline, transmission lines and announced hydrogen PtX projects in Denmark [49], [81], [99], [116].

Based on the GIS analysis the average distance from the announced hydrogen PtX projects to a transmission line and the proposed hydrogen pipelines is respectively 2 km and 21 km. These distances will be used in the further analysis of the cost of transmission line expansion and additional hydrogen pipeline. The distance from the projects to the infrastructure indicates, that the majority of the projects are placed in proximity to existing transmission lines. As the proposed hydrogen pipeline location is not finalized, developers of PtX projects cannot plan for this yet, which can be a reason for the greater distance to the hydrogen pipeline, than the distance to transmission lines.

The analysis is based on the currently announced hydrogen projects as it is assumed, that these areas are favourable for PtX project development, and these areas have been investigated whether they are favourable for an electrolyser or not. In the analysis, it is assumed that all the PtX projects are located on land, and none of them are offshore.

Different electrolyser capacities are found for the scenarios in the analysis in section 5.2.1 to be an additional 5 GW, 10 GW, and 15 GW compared to the IDA baseline scenario. The average size of the announced hydrogen PtX projects is 630 MW [81] and based on this, the numbers of PtX projects are decided. It is however acknowledged that the size of PtX projects might be larger than the average size of the current announced projects in the future, but this number is used to include the infrastructure expansion costs. By basing the size of PtX projects on the currently announced capacity of the projects, the cost of the infrastructure might be higher than it will be in the future. If the future projects have a larger capacity than the currently announced, more PtX projects are included in the analysis than there might be. This is due to the fact, that if the PtX projects in the future have a large capacity, transmission line and hydrogen pipeline expansion are not needed to the same degree, as if several smaller projects need the expansions. The average size of the 23 announced hydrogen PtX projects is~630 MW, which will be used to calculate the number of new PtX projects in each scenario to accommodate the export of hydrogen:

Scenario 1: 5,000 MW electrolyser capacity addition ≈ *8 projects*
Scenario 2: 10,000 MW electrolyser capacity addition ≈ *16 projects*
Scenario 3: 15,000 MW electrolyser capacity addition ≈ *24 projects*

To conduct the analysis it is furthermore assumed, that all future PtX projects will be grid-connected and connected to a hydrogen pipeline, but this is not necessarily the case in reality. This assumption is made to find the average distance from the announced PtX projects with a minimum capacity of 50 MW to the infrastructure.

The lengths of the new transmission lines and hydrogen pipelines that are found in this section will be used in the following section in the socio-economic analysis.

7.2 Socio-economic Results

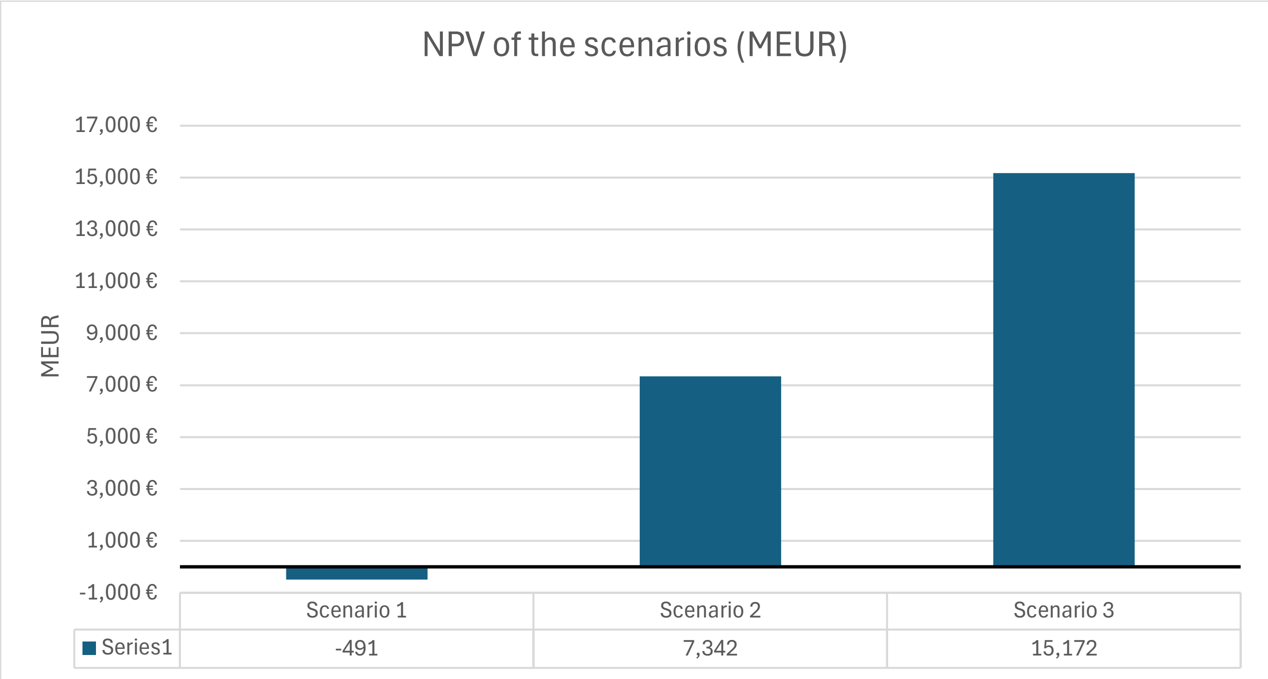
In this section, the results of the socio-economic analysis of the three scenarios will be presented, analysed, and compared with each other. A thorough explanation of the different economic parameters of the socio-economic evaluation is presented in *section 5.1.1*, while the Excel sheet including the calculations is found in *Appendix 12.3*.

The NPV is calculated based on the additional capacities of the technologies compared to the IDA baseline scenario and can be seen in *Table 10*.

	Scenario 1	Scenario 2	Scenario 3
Offshore wind capacity	9.3 GW	16.3 GW	22.9 GW
Electrolyser capacity	5 GW	10 GW	15 GW
Hydrogen storage	385 GWh	745 GWh	1,106 GWh
Fixed hydrogen export	30.75 TWh/year	54.3 TWh/year	77.85 TWh/year
Fuel balance (Natural gas)	6.14 TWh/year	7.52 TWh/year	9.06 TWh/year
Electricity import	8.72 TWh/year	12.31 TWh/year	16.61 TWh/year
Hydrogen pipeline	168 km	336 km	504 km
Electricity line	16 km	32 km	48 km

Table 10: Additional capacities of the scenarios compared to the IDA baseline scenario.

Following *Graph 8* shows the calculated NPVs of the three scenarios. The results of the NPV analysis present that scenario 1 with a 5 GW additional electrolyser capacity has a negative NPV of -491 MEUR, which means that the scenario is not socio-economic feasible with the included parameters. Scenario 2, with an additional 10 GW electrolyser capacity, has a positive NPV of 7,342 MEUR, which means the scenario is socioeconomically feasible. Scenario 3, with an additional 15 GW electrolyser capacity, has a positive NPV of 15,172 MEUR, which means that scenario 3 is socioeconomically feasible.



Graph 8: NPV of the three scenarios.

	Scenario 1	Scenario 2	Scenario 3
Total revenue per year (MEUR)	2,959	5,093	7,228
Total initial investment in year 0 (MEUR)	22,436	39,893	56,492
Cost per year incl. O&M (MEUR)	1,766	2,525	3,322
NPV (MEUR)	-491	7,342	15,172

Table 11: Results of the socio-economic analysis.

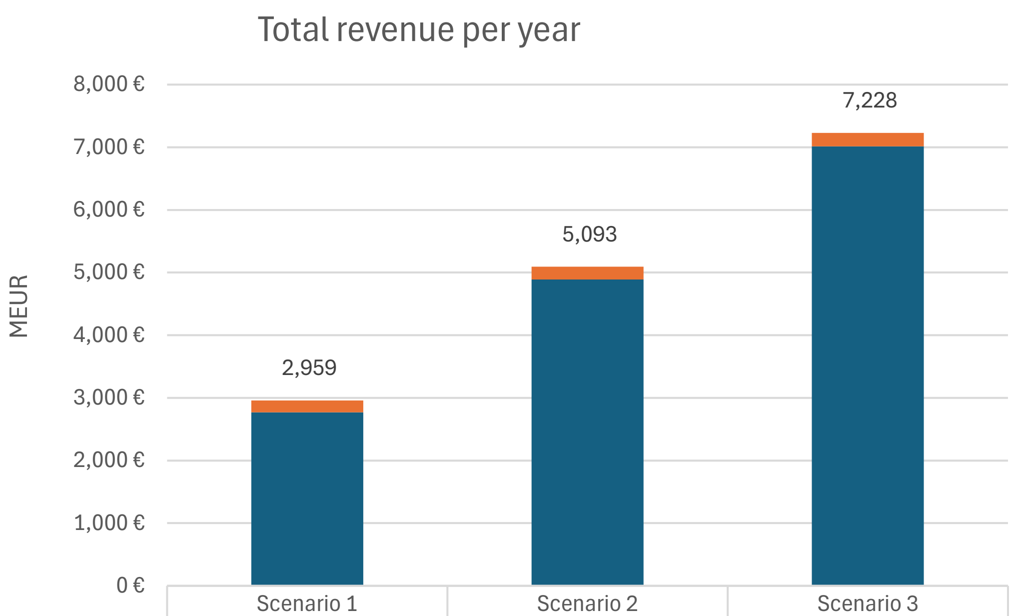
The results of the socio-economic analysis, shown in the above *Table 11*, present the yearly revenue of the three scenarios, the total initial investment in year 0 and the cost per year incl. O&M. Further explanation and calculation of the values in the above table are also shown in *Appendix 12.3*.

The below *Table 12* explains why scenario 1, with the lowest electrolyser capacity, is the only of the three scenarios that are not socioeconomically feasible. The relation between the initial investment and the yearly revenue is the best in scenario 1, but the difference is not significant compared to scenarios 2 and 3, with the same relation. The relation between the yearly revenue and yearly cost is on the other side better in scenarios 2 and 3, compared to scenario 1, which can help explain, why the NPV is negative in scenario 1. The table below shows the cost per year for producing one TWh of hydrogen for export for each of the three scenarios. For scenario 1 the cost per year of producing one TWh of hydrogen for export is 57.4 MEUR, for scenario 2 the cost is 46.5 MEUR and for scenario 3 the cost is 42.8 MEUR. This shows that it is cheaper to export one TWh of hydrogen in scenario 3.

	Scenario 1	Scenario 2	Scenario 3
Relation between total initial investment in year 0 and total revenue per year	7.6	7.8	7.8
Relation between total revenue per year and cost per year incl. O&M	1.7	2	2.2
Cost per year for producing one TWh of hydrogen for export (MEUR)	57.4	46.5	42.8

Table 12: Relation between socio-economic results.

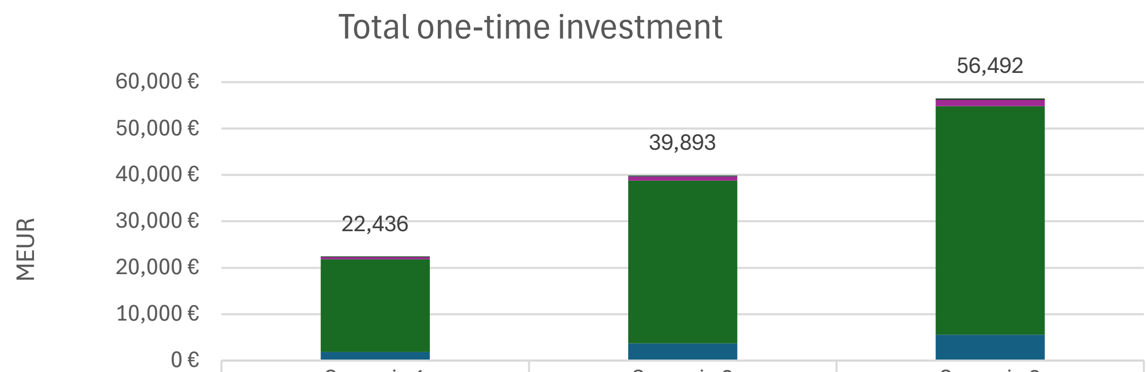
One of the parameters of the socio-economic calculations is the revenue of the scenarios. The total revenue includes the profits of selling the produced hydrogen for export and the profits of exporting electricity. It is shown that scenario 3 has the highest total revenue of the three scenarios, which is expected as scenario 3 has a higher export of hydrogen. The different numbers included in the yearly revenue for each scenario are presented in the following *Graph 9*. The graph shows that the hydrogen offtake price constitutes the greatest yearly revenue.



	Scenario 1	Scenario 2	Scenario 3
Export of electricity spot price	189	201	215
Hydrogen offtake price	2,770	4,892	7,014
Total revenue for per year	2,959	5,093	7,228

Graph 9: Total revenue per year for each scenario.

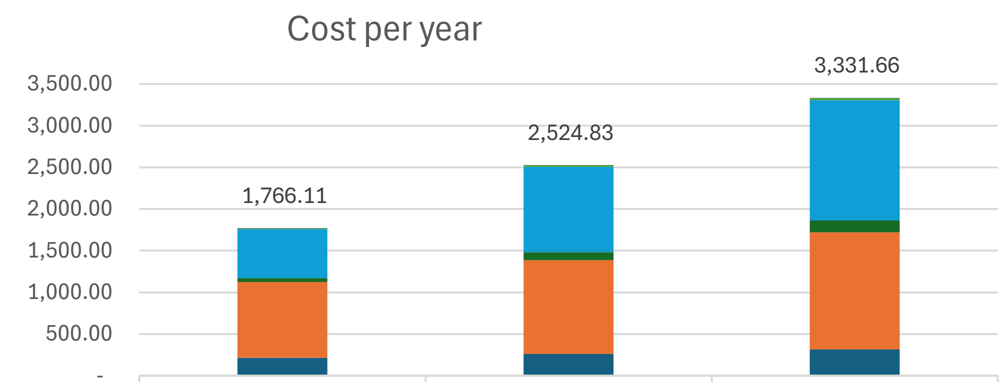
The above *Table 11* also presents the total initial investment in year 0, which includes the investment of the electrolyser capacity, offshore wind turbines, hydrogen storage capacity, electricity distribution network and hydrogen pipelines. In the below *Graph 10* it is clear that the scenario with the highest one-time investment is scenario 3, which is connected to the higher investments in a larger electrolyser capacity, larger offshore wind turbine capacity and investment in hydrogen pipelines. From the below graph, it is also evident that the parameter that constitutes the greater part of the one-time investment is the investment in additional offshore wind turbine capacity followed by the investment of additional electrolyser capacity.



	Scenario 1	Scenario 2	Scenario 3
Hydrogen pipelines	93	185	278
Electricity distribution	0.63	1.27	1.90
Hydrogen storage	492	951	1,412
Offshore wind turbine	19,999	35,052	49,244
Electrolyser	1,852	3,704	5,556
Total one-time investment	22,436	39,893	56,492

Graph 10: Total one-time investment for each scenario.

The below Graph 11 presents the cost per year for each scenario, also known as the annual cost of the scenarios, which is the cost that occurs each year of the lifetime of the project. This includes the price of importing electricity to the system and the price of natural gas consumption. On top of this, the cost per year of the scenarios also includes the fixed and variable O&M of the electrolyser, offshore wind turbines, hydrogen storage, electricity distribution network and hydrogen pipelines.



	Scenario 1	Scenario 2	Scenario 3
Hydrogen pipes O&M	0.15	0.53	1.14
Electricity distribution O&M	8.45	16.91	25.36
Hydrogen storage O&M	0.00	0.00	0.00
Offshore wind turbines O&M	585.14	1,026.66	1,442.95
Electrolyser O&M	47.41	94.81	142.22
Import of electricity	911.43	1,124.39	1,404.91
Price of natural gas consumption	213.53	261.52	315.07
Total cost per year	1,766.11	2,524.83	3,331.66

Graph 11: Cost per year for each scenario.

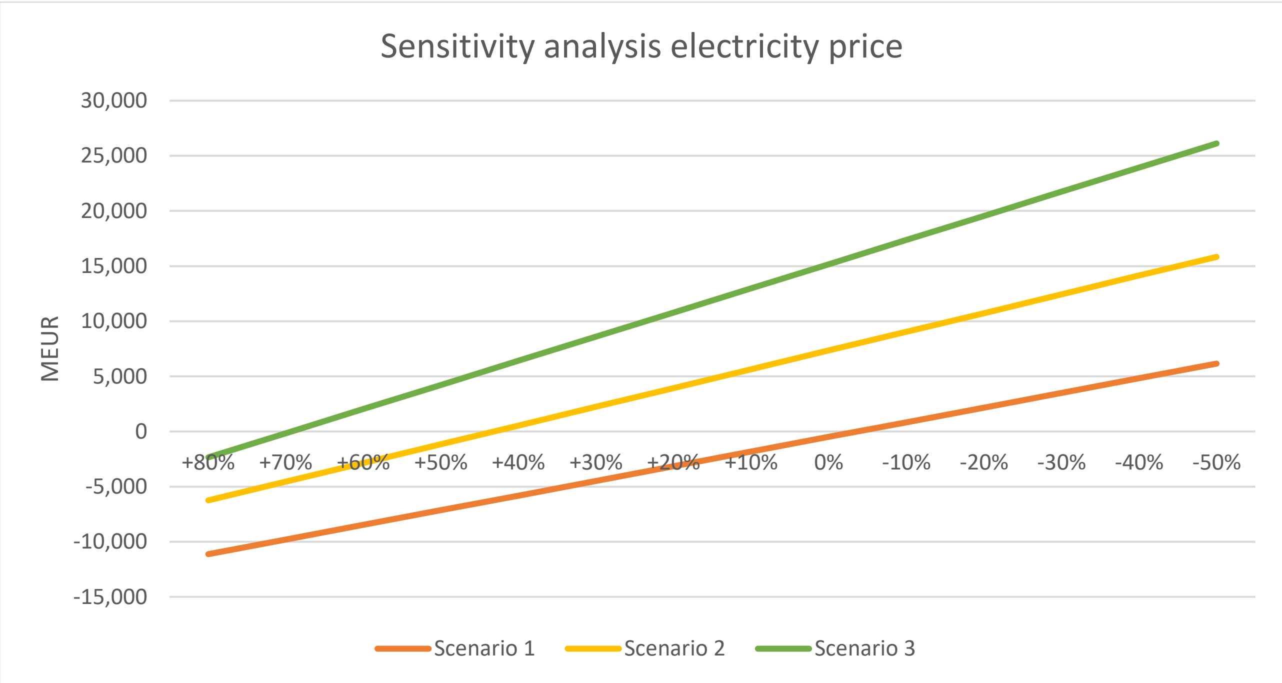
The scenario with the highest cost per year is scenario 3. This can be explained by the higher O&M costs that follow including a larger electrolyser and offshore wind turbine capacity. The price that constitutes the greatest amount in the total cost per year for all three scenarios is the O&M cost for the import of electricity. Following this is the price of the offshore wind turbines, which also constitutes a large part of the total cost per year.

7.3 Sensitivity Analysis

In this section, three sensitivity analyses will be presented. This is the analysis of the hydrogen price, electricity price, and investment cost of the offshore wind turbines. The economic parameters have been mentioned by several interviewees as the economic parameters that constitute the main reasons for not having a feasible business case. The sensitivity analyses will be conducted to investigate the appropriate price level for the NPV to be positive and therefore the scenarios to be socioeconomically feasible. The specific calculations of the sensitivity analyses can be seen in *Appendix 12.3*.

7.3.1 Electricity Price

The first sensitivity analysis is of the electricity price. The electricity price is used in the socio-economic calculations when calculating the revenue of exporting electricity from the system and the cost of importing electricity to the system. The electricity price used in the socio-economic calculations is of hourly values for an entire year. When conducting the sensitivity analysis all prices in all 8760 hours are changed with a percentage interval of 10%. Following *Graph 12* and *Table 13* shows the results of the sensitivity analysis.



Graph 12: Sensitivity analysis of the electricity price.

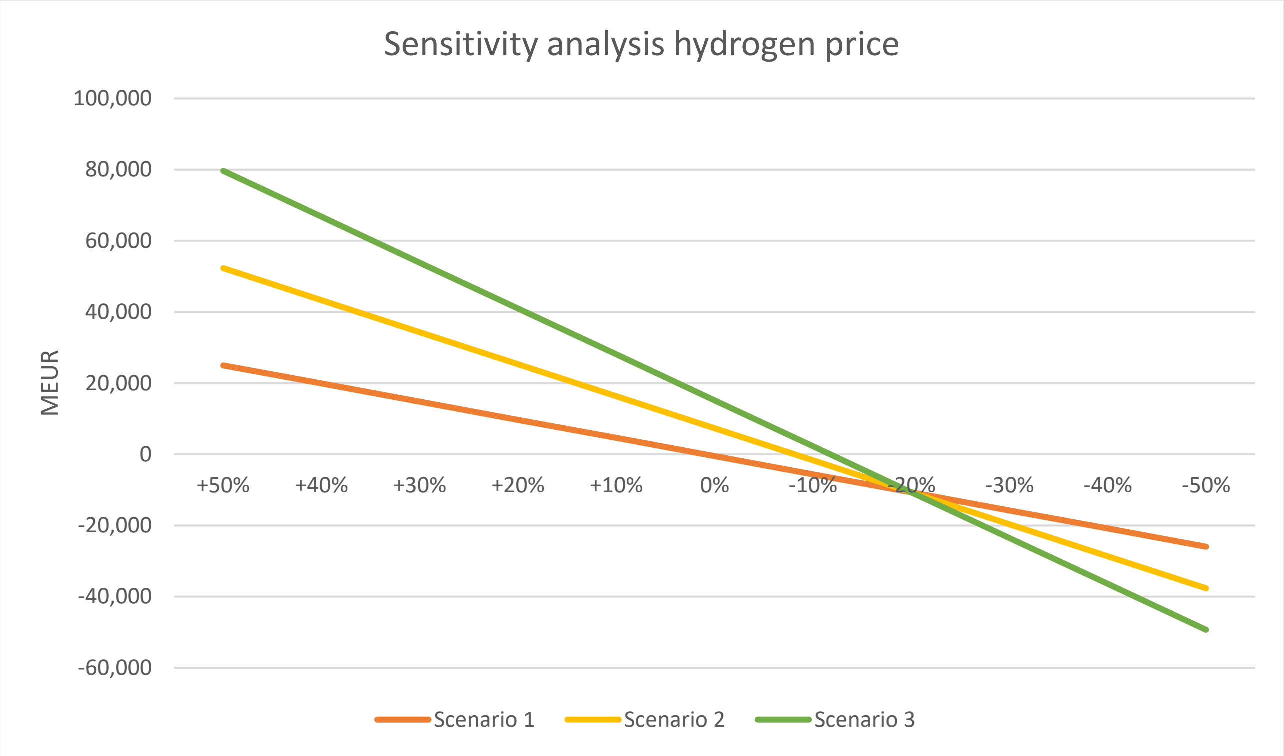
The results of the sensitivity analysis of the electricity price show that for scenario 1 to be socioeconomically feasible and have a positive NPV, the electricity price must be reduced by 10%, which equals an average electricity price of 45 EUR/MWh. From *Graph 12* and *Table 13* it is clear that scenario 2 will have a positive NPV until the electricity price is increased by approximately 50%, which is equivalent to an average electricity price of 75 EUR/MWh. Likewise, scenario 3 will have a positive NPV until the electricity price is increased by 70%, which is equivalent to an average electricity price of 85 EUR/MWh

	Average electricity price (EUR/MWh)	Scenario 1	Scenario 2	Scenario 3
+80%	90	-11,126	-6,247	-2,347
+70%	85	-9,797	-4,549	-158
+60%	80	-8,468	-2,851	2,032
+50%	75	-7,139	-1,153	4,221
+40%	70	-5,810	546	6,411
+30%	65	-4,481	2,244	8,600
+20%	60	-3,152	3,942	10,790
+10%	55	-1,823	5,641	12,979
0%	50	-491	7,342	15,172
-10%	45	835	9,037	17,358
-20%	40	2,164	10,735	19,548
-30%	35	3,493	12,434	21,737
-40%	30	4,822	14,132	23,927
-50%	25	6,151	15,830	26,116

Table 13: Overview of the sensitivity analysis of the electricity price.

7.3.2 Hydrogen Price

This sensitivity analysis is of the hydrogen price, which is used in the socio-economic analysis to calculate the revenue of selling the produced hydrogen from the electrolyser. It has been chosen to do a sensitivity analysis on the hydrogen price as this is one of the essential economic parameters of PtX projects that the interviewees highlighted, and as seen in Graph 9: Total revenue per year for each scenario. it is the primary source of revenue in the socio-economic analysis. The price of hydrogen used in the analysis and the price which the sensitivity analysis is based upon is 3 EUR/kg [89]. Following *Graph 13* and *Table 14* shows the results of the sensitivity analysis.



Graph 13: Sensitivity analysis of the hydrogen price.

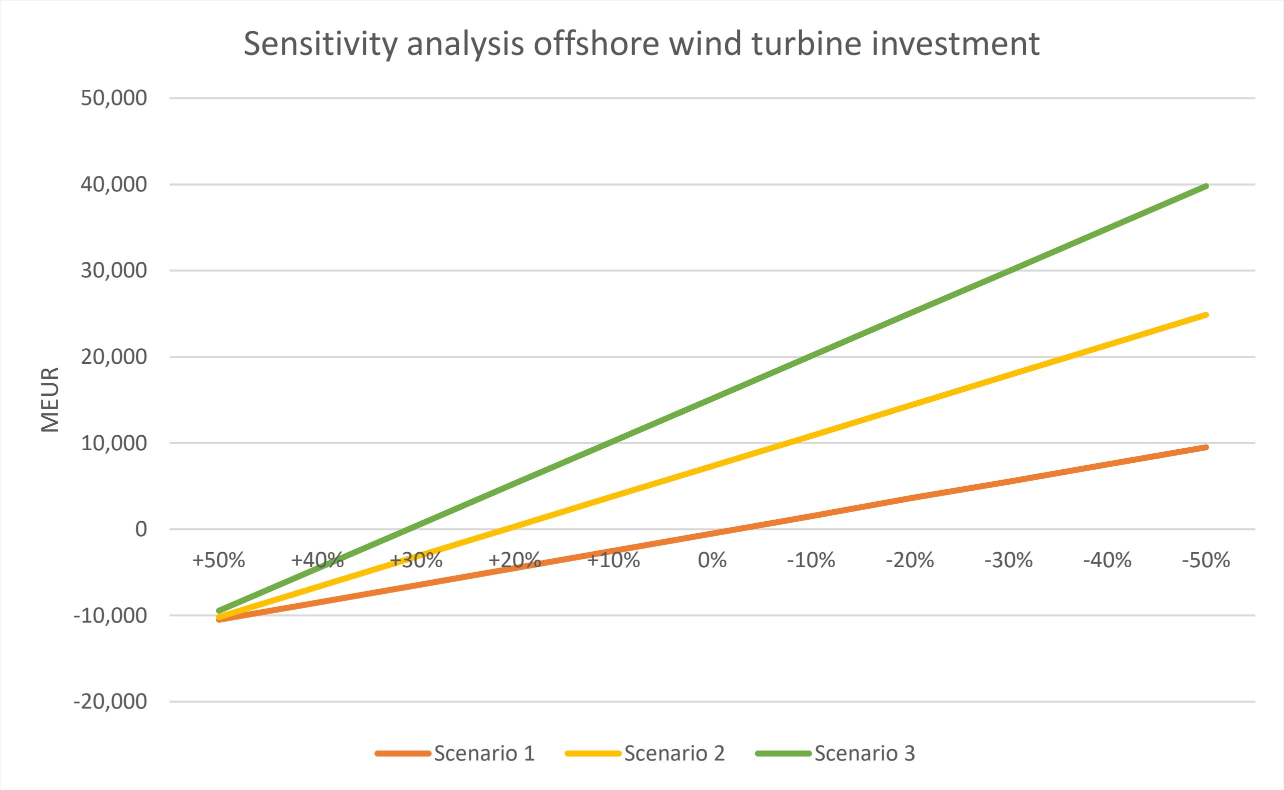
The results of the sensitivity analysis show that to encounter a positive NPV in scenario 1, and for the scenario to be socioeconomically feasible, the hydrogen price should be increased by approximately 10%, which equals a hydrogen price of 3.3 EUR/kg. On the other end of the scale, the sensitivity analysis shows that scenario 2 will be socioeconomically feasible until the hydrogen price is reduced by approximately 10%, equivalent to a hydrogen price of 2.7 EUR/kg. Likewise, scenario 3 will be socioeconomically feasible until the hydrogen price is reduced by approximately 20%, equivalent to a hydrogen price of 2.4 EUR/kg. This sensitivity analysis also shows that at a reduced hydrogen price of 20% where the price is 2.4 EUR/kg, all three scenarios are almost at the same NPV value, and when reducing the hydrogen price further scenario 3 will become the scenario with the lowest NPV and scenario 1 will become the scenario with the highest NPV.

	Hydrogen price (EUR/kg)	Scenario 1 NPV (MEUR)	Scenario 2 NPV (MEUR)	Scenario 3 NPV (MEUR)
+50%	4.5	24,985	52,328	79,668
+40%	4.2	19,889	43,331	66,769
+30%	3.9	14,794	34,334	53,870
+20%	3.6	9,699	25,336	40,971
+10%	3.3	4,604	16,339	28,071
0%	3	-491	7,342	15,172
-10%	2.7	-5,586	-1,655	2,273
-20%	2.4	-10,681	-10,652	-10,627
-30%	2.1	-15,776	-19,650	-23,526
-40%	1.8	-20,871	-28,647	-36,425
-50%	1.5	-25,966	-37,644	-49,324

Table 14: Overview of the sensitivity analysis of the hydrogen price.

7.4 Offshore Wind Turbine Investment

This sensitivity analysis is of the offshore wind turbine investment cost. It has been chosen to do a sensitivity analysis on the offshore wind turbine investment cost as it in *Section 7.2* was evident that the initial investment in offshore wind turbines is the dominant one-time investment in all three scenarios. Following *Table 15* and *Graph 14* shows the results of the sensitivity analysis of the offshore wind turbine investment cost.



Graph 14: Sensitivity analysis of the offshore wind turbine investment.

The results of the sensitivity analysis of the investment of the offshore wind turbines show that for scenario 1 to encounter a positive NPV and to be socioeconomically feasible the investment cost must be reduced by 10%. On the other end of the scale, the sensitivity analysis shows that scenario 2 will be socioeconomically feasible until the investment of the offshore wind turbines is increased by approximately 30%, and scenario 3 will be socioeconomically feasible until the investment of the offshore wind turbines is increased by approximately 40%.

	Scenario 1 NPV	Scenario 2 NPV	Scenario 3 NPV
+50%	-10,490	-10,184	-9,450
+40%	-8,490	-6,679	-4,526
+30%	-6,491	-3,173	399
+20%	-4,491	332	5,323
+10%	-2,491	3,837	10,248
0%	-491	7,342	15,172
-10%	1,509	10,840	20,096
-20%	3,590	14,352	25,021
-30%	5,509	17,857	29,945
-40%	7,509	21,363	34,870
-50%	9,508	24,868	39,794

Table 15: Overview of the sensitivity analysis of the offshore wind turbine investment.

7.5 Preliminary Summary

It is through a GIS analysis determined that the average distance from the announced PtX projects to an electricity transmission line and proposed hydrogen pipeline is respectively 2 km and 21 km. It is also determined how many new PtX projects are to be installed in each scenario, to accommodate the increase in electrolyser capacity and hydrogen export. These values are among other economic parameters included in the socio-economic evaluation of the three scenarios of this report. The results of the socio-economic evaluation conclude that scenarios 1 is not socioeconomically feasible when calculated with the chosen economic parameters of the analysis. Scenarios 2 and 3 has a positive NPV, which represents that the scenario is socioeconomically feasible. The fact that scenarios 2 and 3 are socioeconomically feasible can be explained as the relation between the revenue and cost per year increases more than the increase in the initial investment through the scenarios. Along with this, the cost per year for producing one TWh of hydrogen for export is lowest in scenario 3.

Three sensitivity analyses have been conducted: The electricity price, the hydrogen price, and the offshore wind turbine investment. From the sensitivity analysis of the electricity price, it is clear that scenario 1 will be socioeconomically feasible at a decrease in the electricity price of 10%, which equals an average electricity price of 45 EUR/MWh. Scenarios 2 and 3 will have a positive NPV until the electricity price is increased by respectively 50% and 70%. From the sensitivity analysis of the hydrogen price, it is evident that scenario 1 will have a positive NPV at an increase in the hydrogen price of 10% equivalent of a price of 3.3 EUR/kg hydrogen. While scenarios 2 and 3 will have a positive NPV and therefore be socioeconomically feasible until the hydrogen price is reduced by respectively 10% and 20%. Lastly the sensitivity of the offshore wind turbine investment shows that scenario 1 will encounter a positive NPV and be socioeconomically feasible when the investment is reduced by 10%. Following this, scenarios 2 and 3 will in the sensitivity analysis of the offshore wind turbine investment have a positive NPV until the investment is increased by respectively 30% and 40%.

From the socio-economic analysis and the connected sensitivity analyses, it can be concluded that for Denmark to be an exporter of hydrogen the investments and capacities need to follow scenarios 2 or 3 of this report. This means that the electrolyser capacity in 2045 should be 14.8 or 19.8 GW and the offshore wind turbine capacity should be 30.3 or 36.9 GW when the reference is the IDA Climate Response 2045 report, for it to be socioeconomically feasible for Denmark to export hydrogen.

8 Analysis of Regulatory and Framework Conditions

This chapter will analyse which regulatory challenges and means of action stakeholders within the PtX value chain in the Danish PtX business identify, which is compliant with the third sub-question. The chapter is divided into five sections matching the five dimensions of the technology definition: Technique, Product, Profit, Knowledge, and Organisation. The technology definition is further described in *Section 4.2.1* and visualised in the context of PtX in below *Figure 12*. In each of the five sections, the biggest challenges within the PtX industry in Denmark are explored through the interviews in this report. The five sections do not only include the challenges in the PtX industry but also include what the interviewees state as means of action to plan PtX projects.

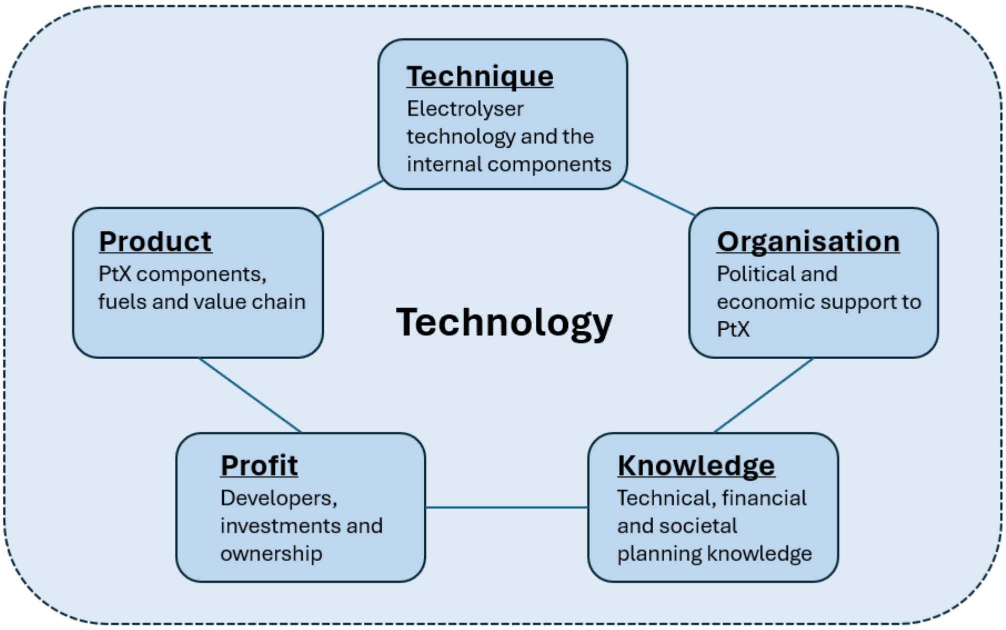


Figure 12: Technology definition in the context of PtX.

8.1 Technique

In the technology definition presented in *Section 4.2.1* the *technique* dimension represents the electrolyser technology and the internal components and their interactions.

One of the challenges presented in the interviews with relevant stakeholders in the PtX value chain is the relatively small-scale production of PtX as of now. A result of the small-scale production is the higher price of the PtX products. Tine Lindgren from Energinet [117] states in the interview that the price of PtX products will probably decrease in the future due to the maturement of PtX products and its technologies, there is a need for large-scale production. Jeppe Grue from COWI [118], Michael Hougaard Sandgreen from the Danish Energy Agency [119] and Søren Hartz from European Energy [120] all agree with Lindgren that the price of PtX products will decrease when the market gets more mature and when there is a larger production. The essential element here is the scale-up in production that is needed.

Key challenges and means of action:

- PtX is a new technology and is only at a small-scale today which increases the price of PtX products → Maturement of technology and large-scale production.

8.2 Product

As presented in *Section 4.2.1* the technology dimension *product* represents the entire PtX components and the value chain from electricity and water inputs to the electrolyser outputs consisting of among others PtX fuels and excess heat.

One of the biggest problems in the PtX value chain is securing enough renewable electricity for the electrolyser to produce hydrogen. Sandgreen [119] states in the interview, that one of the biggest challenges within the PtX business in Denmark is the business case where the securement of the supply chain is especially challenging. Sandgreen [119] states that if there is no electricity there are no PtX projects, and that the projects are also highly dependent on an offtake agreement. Grue [118] follows the critics from Sandgreen and states in the interview, that what he finds as the main challenge with PtX is that there of now is not enough renewable electricity in the system and that it has to be renewable to produce green hydrogen. One of the problems here is that the development of RES has been a bit on hold the last couple of years, especially since the development of offshore wind energy in the North Sea has been slow due to political regards [118]. Grue [118] though finds the new offshore wind tender in Denmark is a positive thing, also the fact that the tender includes further installation than just the 6 GW so that more electricity than the grid can handle can be produced because this creates good conditions for PtX projects. Another challenge in connecting to securing renewable electricity is the development of new electricity transmission lines to accommodate the new production and consumption capacities [118]. Hartz [120] explained in the interview that for the PtX plant to be feasible it is essential to both be connected to the electricity grid and have direct lines to RES, which emphasizes the point from Grue [118] about the importance of expanding the electricity transmission grid to accommodate the implementation of PtX projects.

Another part of the PtX value chain is hydrogen production, where initiating an offtake agreement for the electrolyser to be feasible is essential. Sandgreen [119] highlights the uncertainty of the offtake of hydrogen as one of the main challenges of the PtX industry in Denmark, alongside the need for hydrogen infrastructure. He finds a simultaneous regulation of the offtake side to be preferred, especially on the EU level where the offtake of hydrogen for maritime and aviation can be planned [119]. Lindgren [117] also states that the relatively small offtake market compared to the production side is a challenge and that the offtake side is not as visible. On the offtake side, Grue [118] identify the challenges of the price of hydrogen, and the offtakers must be willing to pay for the fuel. CIP has, for its HØST project, where David Dupont-Mouritzen is co-project director [111], announced after the interview, that they expect to be connected to the German hydrogen backbone in 2028, by a Danish hydrogen pipeline [109], which indicates that stakeholders now make agreements dependent on Danish hydrogen infrastructure.

Mette Kirstine Schmidt and Adriana Guerenabarrena from Brintbranchen [121] highlight in the interview the uncertainty of the hydrogen infrastructure as a big challenge for the PtX industry and state that a hydrogen pipeline is crucial and essential for the development of PtX. Several of the interviewees highlight the uncertainty of when the hydrogen infrastructure will be implemented as a big challenge. David Dupont-Mouritzen from HØST [111] states it is difficult for a developer to depend on a hydrogen infrastructure if you do not know if or when it will be implemented. Following

Dupont-Mouritzen's statement Sandgreen states that the hydrogen infrastructure risks becoming a showstopper if it is not developed in time [119]. Hartz [120] agrees with the others that a hydrogen pipeline only makes sense if you have a timeline and an implementation plan. Schmidt and Guerenabarrena [121] also think that there has been a lack of focus on the national demand for hydrogen and the regional development of hydrogen infrastructure. They find it a problem that the hydrogen infrastructure is not planned on a distribution level, and are nervous about the risks of not knowing the process results [121]. Grue [118] finds the hydrogen infrastructure gives some security for the developers as it ensures better possibilities for offtake agreements, and especially the connection to Germany is positive as they today have a huge demand for hydrogen. Lindgren from Energinet [117], who is responsible for the implementation of the hydrogen infrastructure, explains that Energinet is busy planning for the hydrogen infrastructure in Denmark, but also needs some kind of security regarding how much the infrastructure will be used. Energinet is therefore investigating how much the PtX projects want to commit to using the infrastructure [117]. Lindgren explains that the owners of Energinet have made the criteria that the hydrogen pipeline must be booked with 1.4 GW hydrogen before investments can be made [117]. The expectation is that around 44 % of the hydrogen pipeline should be booked when it is operational [117]. Lindgren expresses, that she understands the risks PtX projects must take when relying on new hydrogen infrastructure, it's the dilemma of the chicken and the egg [117].

Key challenges and means of action:

- Securing renewable electricity → More RES should be developed.
- Securing an offtake agreement for hydrogen → Developing a hydrogen pipeline
- The timelines of the different components in a PtX project do not align → The timeline and implementation of a hydrogen infrastructure must be developed in time to accommodate hydrogen PtX projects.

8.3 Profit

As described in *Section 4.2.1* the profit dimension concerns the change in profit when new developers, organisations, investors, and owners are involved in PtX projects.

From a business case perspective, the biggest problem is that there is no favourable tariff structure for large and flexible consumption and with the current structure it is too expensive according to Dupont-Mouritzen [111]. Dupont-Mouritzen [111] further states that the biggest challenge in general is the price of electricity as the spot prices are too high, and the price of electricity constitutes the largest share of the price of hydrogen. Hartz [120] also agrees that the business case is not feasible if projects are only grid-connected due to the tariffs, but to increase the operational hours of the electrolyser plants, it is optimal if the project is both grid-connected and has direct lines to RES. Dupont-Mouritzen [111] states several solutions to improve the business case. A means of action is removing tariffs for hydrogen producers, as they do in Germany, potentially developing a governmental green investment bank, or giving tax advantages if the project fulfils certain criteria, e.g. by saying those who invest within the next 5 years should not pay high taxes, as they also take the biggest risk and build the market [111].

In general, several interviewees mention the business case as the biggest challenge where the interest rate, supply chain, and electricity prices are included [119]. The Danish Energy Agency can, however, not do anything about the interest rate, but they can guide the stakeholders in the direction of support possibilities like the European Investment Bank [119]. Grue [118] supports the statement that the business case and the value chain are the biggest challenges and it can slow down the speed of the development of PtX projects in Denmark. Hartz [120] states that a mean to decrease the price of PtX products is by making large-scale projects, making the processes more efficient and exploiting the waste products. Sandgreen [119] points out, that a proven business case is important, but there is still a need for larger capital investments. The investments can however be difficult to get as there are a lot of risks concerned with PtX [122].

As the hydrogen pipeline in Denmark has not been developed yet the hydrogen tariffs for using the pipeline are still uncertain [117]. There will possibly be a limit on the tariffs in the beginning to make it more feasible for the first user to connect [117].

As there is no large market for renewable-based hydrogen today it can be difficult to get the consumer to pay an additional price compared to the fossil fuel-based alternative, and it is difficult for the offtakers to know, what the “right” price is [118]. Grue [118] also states that the higher price of renewable hydrogen is a problem, but as the market gets more mature and there is a larger production, the price of the different technologies will probably decrease and thereby also the price of hydrogen. Hartz [120] supports the statement on the challenge of a higher price of renewable hydrogen [120], who further elaborates, that renewable hydrogen cannot compete with Russian natural gas and Australian coal, and most offtakers do not want to pay an additional price than of today.

Key challenges and means of action:

- Too expensive electricity prices when connected to the grid → Change the current tariff structure as it is too expensive.
- The business case is, in general, the biggest challenge → lower tariffs, exploit the waste products, large-scale production and decrease risks.
- Uncertainty regarding the hydrogen pipeline tariffs → Make sure there is a limit on the tariffs for the first users.
- No hydrogen markets → The development of a hydrogen pipeline enhances the business case, and the price of renewable hydrogen must decrease.

8.4 Knowledge

As mentioned in *Section 4.2.1* the knowledge dimension of technology concerns general knowledge of the technical, financial, and societal aspects. This knowledge is related to understanding the general planning and development aspects of the business case when also considering the surrounding energy system, so it aligns with the SES theory of holistic energy planning.

As a lot of the projects are developed in the less populated areas of Denmark, it is important to know the local context of the project, so the projects do not just contribute to the larger cities' energy consumption but also favour the local community [120]. According to Sandgreen [119] another challenge for PtX projects is the approval process as it can take some time to get all of them. He further states that the stakeholders must be better at making different applications, so the approval process can be shortened [119]. There can however be inconsistencies when the approval process starts, as a developer might think it starts with the first call to the authorities, but if the documentation needed for various permits is not in place, the authorities cannot approve an application [119].

Another way to accommodate long approval processes is if the authorities have better coordination and transparency in why they ask for different information and approvals, and what they should be used for [119]. Sandgreen [119] does, however, state that there is a good collaboration across the value chain of PtX and sector coupling. Schmidt and Guerenabarrena [121] back up the statement of good collaboration and state it is especially good with the energy-related authorities, as they know a lot about the business and are open-minded to proposed suggestions and solutions, but non-energy-related stakeholders have their own goals and agendas and do not necessarily prioritize energy and hydrogen aspects [121]. Both Sandgreen [119] and Schmidt and Guerenabarrena [121] agree there in general is a good collaboration between the stakeholders and authorities which is based on trust. There must be good regulation regarding safety, because if one accident happens, other PtX projects might have challenges getting approvals, so it is important to have knowledge of all of the technical aspects and the interactions between the components [119].

Another aspect where the entire value chain is important is in planning and timelines of all of the components as everything happens from scratch and it has to make sense for all of the stakeholders [117]. It can however be difficult to align every aspect of the PtX value chain at the same time [117], as all the different processes and products are dependent on each other [122]. If there is no electricity, you cannot produce hydrogen, and if there is no hydrogen pipeline, the transportation of hydrogen is difficult, so the alignment is important [119].

Key challenges and means of action:

- Long approval process → Stakeholders must be better at making applications and the authorities should have transparency in what they need and why.
- Lack of proven business cases regarding safety → Regulation on safety throughout the entire value chain should be introduced.
- Difficult to align all processes of the PtX value chain → Align the timelines for the development of the different components in the value chain.

8.5 Organisation

As mentioned in *Section 4.2.1* the organisational dimension concerns the political and economic support of PtX, and who oversees the relevant legislation.

From a political point of view, several means of action can be considered and implemented. As PtX is a relatively new technology, an established fuel market is not in place. Markets can, however, be created if political decisions on fuel mixing requirements in the natural gas system are introduced as stated by Hartz [120], or if requirements for the domestic aviation sector are introduced as stated by Schmidt and Guerenabarrena [121]. This statement is supported by Grue [118] as general fuel mixing requirements will create certainty for a sustainable market. As it can be difficult for renewable-based hydrogen to reach the same price levels as the fossil-based alternative, another way to secure an even market is by introducing a CO_2 charge, so it has a price to pollute the environment and there is an incitement not to do so [118]. Sofie Holmbjerg from Energinet [122] also states that framework conditions should be introduced to make the fossil-based alternative more expensive, and make it easier to compare and compete with the fossil-based alternatives.

One of the largest uncertainties and challenges within the organisation dimension is the lack of regulation and regulatory decisions. This is supported by Hartz [120], Lindgren [117], and Holmbjerg [122]. As of now, the only requirements and regulations there is in Denmark are from the EU [121], and the EU regulation is not properly in place for the entire PtX project, but it must be implemented in the future and the authorities might as well beginning to prepare themselves for this regulation

[117]. When the EU adopted the REDIII directive certain criteria appeared such as the RES must be built within a certain timeframe of the development of the PtX projects, creating direction for the stakeholders to follow [118]. Regulation is needed to make sure you use the RE [120] and even though the REDIII is a good thing there is still a risk if developers develop REDIII-compliant projects, and it, for some reason, is changed and other requirements appear [118]. EU has made the framework conditions for the European regulation, but the regulation must, however, be implemented by the individual countries and it can be very time-consuming before new laws and regulations are in place [122]. This statement is supported by Schmidt and Guerenabarrena [121] who state that a lot of work is going into making regulations from scratch and only a small amount of the needed regulation is already in place for hydrogen, but more is on the way. A problem with the current political landscape regarding planning and regulation is, that it often happens in silos, where sector integration is not a part of the planning, but PtX projects must be planned in a holistic way [121].

Besides better regulation, support schemes are according to Schmidt and Guerenabarrena [121] one of the best means of action to promote PtX projects and make the planning of PtX projects in Denmark easier. This is supported by Sandgreen [119] who states some projects will need economic support through support schemes as it is an upcoming market and to help cover the price differences compared to the fossil-based alternatives. Schmidt and Guerenabarrena [121] even state it is a must if Denmark is to reach its climate goals, to invest more in production support schemes. An area where the support schemes have showcased an increase in the development of projects is carbon capture projects, but PtX has not been given the same focus, even though it might accelerate the development of the projects [118].

To ensure a reliable and sustainable market a stable political landscape with few changes throughout time is important to ensure continuous support for PtX [119]. The politicians have good intentions, but they mention a lot of goals and things that should happen, but it is very limited what has been realized in the last couple of years [120]. An example of this is when the Danish PtX strategy was designed, the current government planned on making other strategies on how to handle the offtake side, but then Denmark got a new government, and the other strategies were never made [121]. No one knows how the exact regulation is going to be, which is a challenge [122], and it is important to show more political courage if the development of RE projects has to happen at a certain pace to meet the climate goals, but it is difficult having a process where everything is so carefully processed [118].

Key challenges and means of action:

- Hydrogen produced by RES cannot necessarily compete with fossil fuel-based alternatives → A CO_2 charge and support schemes can be a means of action to decrease the price gap.
- It is a new and uncertain market → Mixing and fuel requirements can create a reliable future market.
- Lack of Danish regulation and regulation mainly on the EU level → Implementation of EU regulation in Denmark and general development of PtX favourable regulation.
- Shifting governments and lack of political action create uncertainties → A stable political landscape is needed.

8.6 Additional Challenges

Besides the above-mentioned challenges and means of action, one of the major challenges the interviewees find in the PtX process is time. This is supported by Sandgreen [119], who states it takes time before things are adopted and worked through, and Hartz [120], who states time is the biggest challenge as the process is very slow and unpredictable, especially for generating assets, and Grue [118], who states time is one of the biggest challenges as the transition moves quite slowly, as it is time-consuming, to develop an entire PtX project.

Besides time, Grue [118] argues that if risks and uncertainties can be reduced, it is more favourable for investors to invest in PtX projects. A favourable and predictable market is also important if more investors are to invest in PtX projects [121]. An important stakeholder to influence a favourable market for PtX is the EU as they can be a huge driver in the PtX transition [121].

As this report concerns hydrogen from PtX, all the interviewees were also asked, what their view is on whether Denmark should be an exporter of hydrogen or not. All the interviewees stated unanimously that Denmark should export hydrogen, except Brintbranchen, as they as a lobbying organisation are not allowed to have an official opinion on this subject. Schmidt and Guerenabarrena [121] do, however, state that we should exploit the Danish resources to provide European demands instead of importing fuels and energy from countries outside of the EU. Grue [118] and Hartz [120] agree that Denmark should be an exporter of hydrogen based on good wind resources. Grue [118] further states Denmark has unique resources compared to the rest of the world, while at the same time, Denmark does not have a large hydrogen demand. This statement is supported by Sandgreen [119] and Holmbjerg [122], who argue that the production of hydrogen in Denmark exceeds the national demand, as there is not a large hydrogen market in Denmark, but there is a large demand for hydrogen in Germany. Both Dupont-Mouritzen [111] and Lindgren [117] agree with the statement that Germany has a large market for hydrogen especially in their industry, and will be the largest offtaker of Danish-produced hydrogen in the future.

Key challenges and means of action:

- PtX projects are time-consuming → Maturement of planning/regulatory processes
- Too many uncertainties and risks regarding PtX projects → Make the market more favourable and predictable to navigate in.

8.7 Summary and Comparison of Statements with Current Literature

An overview table of the challenges and means of action statements from the interviewees and the analysis based on the technology definition can be seen in *Table 16*.

	Challenges/barriers	Means of action
Technique	• PtX is a new technology and is only at a small scale today which increases the price of PtX products.	• Maturement of technology and large-scale production.
Product	• Securing renewable electricity • Securing an offtake agreement for hydrogen	• More RES should be developed. • Developing a hydrogen pipeline • The timeline and implementation of a hydrogen infrastructure must

	• The timelines of the different components in a PtX project do not align.	be developed in time to accommodate hydrogen PtX projects.
Profit	• Too expensive electricity prices when connected to the grid. • The business case is, in general, the biggest challenge. • Uncertainty regarding the hydrogen pipeline tariffs. • No hydrogen markets.	• Change the current tariff structure as it is too expensive. • Lower tariffs, exploit the waste products, large-scale production and decrease risks. • Make sure there is a limit on the tariffs for the first users. • The development of a hydrogen pipeline enhances the business case, and the price of renewable hydrogen must decrease.
Knowledge	• Long approval process. • Difficult to align all processes of the PtX value chain. • Lack of proven business cases regarding safety.	• Stakeholders must be better at making applications and the authorities should have transparency in what they need and why. • Regulation on safety throughout the entire value chain should be introduced. • Align the timelines for the development of the different components in the value chain.
Organisation	• Hydrogen produced by RES cannot necessarily compete with fossil fuel-based alternatives. • It is a new and uncertain market. • Lack of Danish regulation and regulation mainly on the EU level. • Shifting governments and lack of political action create uncertainties.	• A CO_2 charge and support schemes can be a means of action to decrease the price gap. • Mixing and fuel requirements can create a reliable future market. • Implementation of EU regulation in Denmark and general development of PtX favourable regulation. • A stable political landscape is needed.

Others	• PtX projects are time-consuming. • Too many uncertainties and risks regarding PtX projects.	• Maturement of planning/regulatory processes • Make the market more favourable and predictable to navigate in.

Table 16: Overview table of the challenges and means of action based on the interviews and the technology definition.

Based on the above analysis the different challenges regarding PtX are highlighted based on the interviews with relevant stakeholders. It is acknowledged, that different answers might have appeared if other stakeholders were interviewed. To summarise, the largest challenges regarding PtX are: New technology, secure renewable electricity, grid tariffs, offtake and the price of hydrogen, hydrogen infrastructure, business case, new and uncertain hydrogen market, regulation, timing and alignment of all processes, and general uncertainties. These challenges both represent barriers from a socio-economic point of view and a business case point of view.

The challenges identified by the interviewees, align with the identified challenges in *Section 2.4.2.* The challenges in *Section 2.4.2* concern not enough affordable and available electricity from RES in the future, which aligns with challenges identified in the product and profit dimensions. Another challenge identified in the current literature in *Section 2.4.2* is that it is an uncertain market and conditions, and regulations must be approved. This aligns with the organisational dimension. In *Section 2.4.2* the lack of hydrogen infrastructure is also highlighted as one of the biggest challenges, which aligns with the product, profit, and knowledge dimensions.

The statements from the interviewees furthermore align with the stakeholder forum from the Danish Energy Agency [123]. The stakeholder forum consists of stakeholders within the PtX value chain who know of, amongst other things, barriers and possibilities, and the development of PtX [124]. Here some of the main barriers and means of action to the development of PtX in Denmark are addressed to be, clarity regarding the hydrogen infrastructure, access to electricity, access to CO_2 and a CO_2 market, the business case including certainty regarding economic frames and fast implementation of regulation, authority processes, offtake including regulation and other means to lower the prices, tariffs connected to the electricity, and access to water to PtX. All of these barriers and means of action align with the statements of the interviewees and the technology definition as all five dimensions are covered.

9 Discussion

This chapter aims to discuss the defined conditions for the analysis of this report alongside the use of methods and theories and the uncertainties that are in the analysis. This chapter will also discuss the results of the analyses and how changes to the parameters in the analysis might affect the results. The barriers and means of action in the framework conditions of PtX presented in the analysis will also be discussed. Finally, future perspectives of the PtX industry are discussed and the role PtX has in the future.

9.1 Analysis Prerequisite and Usage

The result of the analysis depends on the local resources, prerequisites, and conditions. Planning is often related to the future, and uncertainties naturally occur due to that. An uncertainty in this analysis is the general energy infrastructure, as the hydrogen pipeline and transmission and distribution line might have been expanded and built in the future. The analysis in this report is based on 2024 estimations on how the infrastructure, prices and different components will be in 2040, but numerous things can change during the coming 20 years. Reality is often more complex than theory, as energy policies and regulations play an important role in how RE should be prioritised and utilised. Several unplanned factors can also affect the potential hydrogen export potential, which is important to keep in mind when making conclusions based on the analysis. The analysis is, however, conducted based on the most recently published numbers for 2040 and 2045. It is acknowledged that these numbers have uncertainties, as they are only projections and not exact numbers of how they will be in 2040 and 2045. This uncertainty is difficult to eliminate, but when planning the future energy system, it is often with data, that are predictions and the best possible numbers for the future.

The hydrogen price used in this report is 3 EUR/kg. It is assumed that hydrogen prices will decrease when the market gets more mature, and more projects are developed. The lower hydrogen price does, however, make the results of the socio-economic calculation more conservative, than if a higher number was used, as the earnings from the hydrogen would be higher if a higher number is used. If a higher hydrogen price was used in the analysis, the NPV of scenario 1 could have been positive depending on the price, as shown in the sensitivity analysis. As a lot of uncertainties are connected to the future hydrogen market, the hydrogen price will probably be within a certain range, depending on the PtX project and the offtaker, and it is, therefore, difficult to know, what the exact price of the hydrogen will be in the future.

The theory of radical technology change and technology definition is combined with the conducted interviews to identify regulatory challenges and potential means of action. The stakeholders for the interviews are selected based on their role in a PtX project, and to cover stakeholders in different phases of the value chain. A stakeholder that could have been interviewed is a municipality, as municipalities must be involved in the location of energy infrastructure projects and make potential changes in the local plan. A municipality is not interviewed in this report, as it is assumed, they operate within the regulation set by the Danish Energy Agency, and this report focuses more on the national level than the local level. It would, however, have been interesting to identify the challenges a municipality faces when working with PtX-related projects and if they identify other challenges, than the national authorities. The role of the municipality in a PtX project is more indirect, as they do not develop the project, but their role is to ensure the right circumstances are in place, to continue the planning. If a PtX project is developed in a proactive municipality that already has made analyses for potential locations of PtX projects, a biogenic CO_2 screening, and wants to focus on the development of PtX projects, it is of course advantageous for a developer to develop a PtX project in that municipality. Another stakeholder that would have been interesting to interview, is a stakeholder from the offtake part of the value chain. This stakeholder could have provided valuable information on what an offtaker finds as the biggest barriers within hydrogen PtX projects. Maersk was contacted, so an interview with a potential offtaker could have been conducted, but they did not return. The offtake perspective of a PtX project, is, however, not the focus of this report, which is why other potential offtakers than Maersk were not contacted. It is acknowledged, that the offtake side of PtX projects is important and is a crucial part of the value chain, which is why elements such as the price of hydrogen and the lack of a proper hydrogen market are included in the analysis.

In the analysis of this report, the existing transmission grid in 2024 is used and potential planned expansions are not included. When measuring the distance from the announced hydrogen PtX projects to the existing grid to an average of 2 km, it is assumed the potential expansions will not have affected this result drastically. A way an expansion of the electricity grid could have affected the results of the analyses is if more connections to the surrounding countries were added, as this might have added more import/export capacity, affected the CEEP value, and the hours where import/export is occurring. As the future energy system and different sectors should be based on electricity, the electricity grid will most likely expand towards 2045 to handle all the additional electricity for electrification and PtX, but this aspect is not included in the analysis. If the expansion of the electricity grid was included in this report, the result of the NPV depends on the assumptions behind it. If it is assumed that the expansion of the electricity grid is an investment in 2040, the investment and O&M should be included in the analyses, and the NPV would most likely be lower than now. If, on the other hand, it is assumed the expansions have been made before 2040, and the investment cost is not included in the calculations, the NPV depends on the operation of the electrolyser and offshore wind turbines, as more electricity can both be imported and exported.

A prerequisite of the analysis is also that all the electrolysers and wind turbines are connected to the grid. This is not necessarily the case, as some of the electrolysers might be supplied with electricity through direct lines from the offshore turbines, and the developer should thereby not pay tariffs. If the analyses were not based on all the electrolysers and offshore wind turbines being grid-connected, it would have affected the business case, as tariffs should not be paid. Direct lines instead of grid-connected projects, would have affected the NPV in a way, that the investments in expanding the grid were not needed. It is, however, assumed, that this cost will not have changed the NPV drastically.

9.1.1 Energy Modelling and Socio-economic Results Discussion

For the analysis of this report, it has been decided to continue with a configuration of hydrogen export of 75% fixed hydrogen export production and the rest connected to the CEEP in the system. The decision to let some of the hydrogen export follow the CEEP in the system was taken to potentially increase the production of hydrogen for export. The theoretical standpoint was that when the electrolyser capacity in the scenarios would increase the hydrogen export would likewise increase. Alongside this, when increasing the offshore wind turbine capacity, the CEEP would theoretically increase in the system. This was though not the case in the scenarios of this report. This is due to the decision to keep the CEEP low in all three scenarios on the same level as the baseline scenario. This means that the offshore wind turbine capacity was not allowed to be increased to a level where the CEEP value would increase compared to the value of the baseline scenario. From investigating different configurations of the scenarios, it could be concluded that to have a high CEEP that would result in a higher hydrogen export, the capacity of the offshore wind turbines must have been much higher.

During the analysis of this report, offshore wind turbine capacities in the different scenarios have been determined along with the areas the offshore wind turbines would require. This is all shown on *Figure 10* where three areas are visualised in the Danish North Sea. The visualisation in this report is only made to get an understanding of the area needed for the offshore wind turbine capacities in the scenarios and does, therefore, not represent where the areas should be in reality. If e.g. a 36.9 GW offshore wind turbine capacity were to be installed as of scenario 3, the turbines would be split into several smaller fields or projects spread over all of the Danish offshore territory. On top of this, getting consent for such a big area in the North Sea would be close to impossible. To realise the scenarios presented in the analysis of this report it is assumed that all offshore wind turbines are to be installed and in operation at the same time. This is not reasonable, as the turbines would be split into several projects planned by different developers who undoubtedly will have different timelines for their projects. The projects will most likely be accepted through different tender rounds, which makes it doubtful for all offshore turbines to be implemented at the same time.

A parameter included in the scenarios that gives some uncertainty to the results is the length of the hydrogen pipelines used in the socio-economic calculations. Through a GIS analysis lengths of hydrogen pipelines from announced hydrogen PtX projects to the upcoming Danish hydrogen backbone have been analysed with an average length of 21 km. The uncertainty of this is, that the already planned PtX projects did not know of the Danish hydrogen backbone before choosing a location for the plant. This means that the PtX plants may have been placed less optimal for connecting to the pipeline. After revealing the Danish hydrogen backbone, new projects will now have the possibility to find more optimal locations for their plants to minimize the length of additional hydrogen pipelines that need to be invested in. The use of the average hydrogen pipeline length of 21 km gives uncertainty to the calculations if they were to be used in the future, as the length of the pipeline is predicted to be shorter in the future.

One of the biggest contributors to both the one-time investment and the cost per year is the offshore wind turbines. This includes both the initial investment in the turbines in year 0 and the O&M cost of the turbines each year of the lifetime of the scenarios. Offshore wind turbines have high investment and O&M costs compared to e.g. onshore wind turbines because the capacities of the turbines are bigger which equals bigger turbine constructions, and the offshore foundations are bigger compared to the onshore foundations [84]. It is also more difficult to install the turbines offshore as it needs to be done by ship and the weather conditions are a determining factor. It might have been cheaper for the scenarios if onshore wind turbines and/or PV had been included instead of only installing offshore wind turbines. Installing RES on land would, however, just have resulted in other problems regarding acceptance from the local community, getting the project approved and installing more onshore turbines than offshore turbines as the onshore turbines have smaller capacities. An advantage of potentially including PV capacity in the scenarios is that it would have been possible to get more operational hours in the electrolyser without having to import electricity. This is because the electrolyser only operates when there is electricity from the turbines or when electricity is imported. The electricity from the offshore wind turbines is restricted only to be present when there is enough wind. The electricity production from PV would be able to support the electricity production from the offshore wind turbines, as the PV can produce when the sun is shining and there might not be enough wind for the turbines to produce electricity. A side effect of including PV in the system is that there might be an overproduction of electricity in hours when there is both wind and sun, which will result in an export of electricity and CEEP.

9.1.2 Barriers and Means of Actions in the Framework Conditions of PtX

The modelling and economic aspect of the analysis takes its point of departure at the societal level by calculating the socio-economy. Even though an analysis of PtX projects is socioeconomically feasible it does not necessarily mean, that the individual PtX plant has a positive business case, as other factors impact the business case than the socio-economic calculations. One of the biggest challenges regarding the business economy, and what several of the interviewees state, is the tariffs concerning the electricity prices when buying electricity from the national grid. The regulation and framework condition analysis found that PtX projects are, in most cases, not economically feasible if the project is connected to the grid. This cost and barrier are not identified when a socio-economic analysis is made, as electricity tariffs are not included in the method of calculating socio-economy. This creates dilemmas and disagreements depending on where in the value chain the stakeholder is and whether the focus is on business- or socio-economy. Authorities who make socio-economic calculations might conclude, that PtX is economically feasible, while the individual developers of PtX plants might disagree, as they have several other costs included in their business economic calculations and the business economic calculation might therefore conclude, that the PtX project is not economically feasible. Developers of PtX projects and other stakeholders point out, as analysed in the regulation and framework condition analysis, that subsidies, lower taxes, or other support schemes will be beneficial to politically introduce to accommodate the business case. A feasible socio-economic analysis reflects that the project is good for the society and might therefore affect politicians to introduce subsidies or tax reductions to make the project feasible from a business economic perspective.

Another important element of both the business and societal perspective is the price of hydrogen as this constitutes a large share of the income and thereby affects the NPV. As other costs are included in business economic calculations, the price of hydrogen might be even more crucial and more fragile towards changes, than from a socio-economic point of view. As different aspects are included in the business and socio-economic calculation, one cannot necessarily conclude, that PtX projects are economically feasible based on just one of the analyses as it depends on the point of view.

As several stakeholders point out in the interviews, PtX is a relatively new business area, and the market and framework conditions are currently associated with uncertainties and risks. These uncertainties and risks must be handled, to create a reliable market, but the problem is, that PtX is a new business for all the stakeholders, both the authorities and the developers, so the industry must be developed from scratch and without a lot of experience. Some experiences are already in place from other businesses like the natural gas distribution, but PtX must be planned holistically, so several sectors must be included. This aligns with the SES theory regarding sector integration, and instead of planning for the individual sectors, the sectors should be planned from a SES point of view, as the sectors and areas of planning are dependent on each other and can benefit from each other.

To limit risks and support a PtX market, mixing requirements in e.g. industries, aviation fuels and the maritime sector is a great means of action to implement, as this ensures a reliable and stable market for PtX fuels. By doing so, risks are reduced for the investors, and they can be more willing to invest in PtX projects, as the offtake side is more certain. Even though a reliable market for PtX fuels can be created, it does not eliminate the challenges of having higher prices of hydrogen produced by RES than from the fossil fuel alternatives. A mean to ensure a comparable market for hydrogen produced from RES and fossil fuels is to introduce a CO_2 charge on the fossil fuels. By doing so developers have an incitement for producing hydrogen from RES and the pollution from fossil fuels will hopefully also decrease, which favours the environment and the climate goals. The implementation of a CO_2 charge on fossil fuels should be implemented by the Danish politicians, just as potential subsidy schemes also can be implemented by the politicians. The CO_2 charge and subsidy scheme both affect the competitiveness of renewable-produced hydrogen, as the CO_2 charge increases the price of fossil-produced hydrogen, and the subsidy scheme can lower the price of renewable-produced hydrogen.

From a political point of view, one of the most important means of action is proper regulation. It can on the other hand be difficult to implement the regulation within a relatively short timeframe, as PtX is a new business, and some aspects might be unknown. Regulation is, however, important before PtX can be widespread in Denmark and globally, as developers and other stakeholders need proper guidelines so they know which guidelines they should fulfil and navigate within. As PtX concerns several sectors and areas, different regulations must be developed. Some of the regulation concerns safety, wastewater, and the environment, which are not directly connected to the development of the PtX project and the technologies, but this regulation is still important to have in place, as it affects parts of the PtX project.

To strengthen the business case of the Danish hydrogen PtX projects and to accommodate Denmark exporting hydrogen, a hydrogen pipeline is crucial. The hydrogen pipeline is in the early-stage planning process, but as more hydrogen PtX projects are developing, certainty on the exact location of the pipeline is important. As mentioned before the HØST project in Esbjerg has already made agreements with a German offtaker, where they are dependent on the hydrogen pipeline. Suppose the hydrogen pipeline for any reason is not developed, this has a huge impact on the HØST project, but also on the Danish hydrogen projects in general, as the hydrogen pipeline is an easy offtake transportation opportunity. The hydrogen pipeline also enables the export of high quantities of hydrogen to the German market, where they have a large demand for hydrogen. As Denmark does not have a large demand for hydrogen, the hydrogen pipeline is crucial to be realised both for the export opportunity Denmark has, due to strong wind resources, the hydrogen PtX projects, and the national climate goals. Even though several stakeholders request the hydrogen pipeline, Energinet will also have to be sure that the hydrogen projects will connect to the pipeline, so there is also a discussion on who should take the risk. If Energinet just develops the pipeline and developers do not want to be connected to it anyway, they face huge economic losses when it is operational. A way to accommodate this risk is to make contracts with developers of hydrogen projects before the pipeline is built. However, this will be a risk for the developers, as they cannot be certain when and if the pipeline is operational.

As the PtX value chain consists of several parameters such as RES, the electrolyser, the electricity grid, the hydrogen pipeline, and an offtake, it can be difficult to ensure all timelines align. When centring the hydrogen PtX projects around the electrolyser, enough electricity from RES is important to produce the hydrogen, and a hydrogen pipeline is important to offtake the hydrogen. It would be ideal if both RES, PtX projects and the hydrogen pipeline were developed, so they are all operational at the same time, but this is not likely to happen. It takes time to develop the RES, and all the electricity is not necessarily exclusively used for PtX projects unless there is a direct line between the PtX project and the RES. Enough electricity from RES is crucial to meeting the climate goals, as several sectors should be electrified. On top of that is the huge demand for electricity for PtX projects. If the hydrogen pipeline is not developed the hydrogen PtX projects must find other offtake opportunities, and if the hydrogen projects are operational before the hydrogen pipeline, they will also have to find other offtake opportunities until the pipeline is operational.

9.2 The Future of PtX

As PtX plays an important role in reaching the national and global climate goals it is an important part of the future energy system. This report focuses solely on hydrogen as the end product of PtX, but other products such as ammonia and methanol can also be the end product of a PtX project if the hydrogen is further converted. If the hydrogen infrastructure is not in place, the developers of the projects might decide to produce other e-fuels. If PtX projects are planned to further convert the hydrogen, the hydrogen infrastructure is not as relevant, compared to if many hydrogen PtX projects are planned. If the report and analysis included ammonia and methanol, different aspects would have to be included such as the availability of biogenic CO_2 sources, and a potential CO_2 infrastructure, if it is a methanol project, and the availability of nitrogen if it is an ammonia project. A lot of the announced PtX projects are, however, planned to have hydrogen as their end-product in Denmark, which is why it is the focus of this report and ammonia and methanol are excluded.

An assumption in this report is, that the PtX projects are planned on land and not offshore. As seen with the proposed energy islands in Denmark, PtX projects might be located offshore. The energy island in the North Sea of Denmark is, however, on hold as of now, but the project still indicates, that hydrogen production might also happen offshore in the future. The advantage of having PtX offshore is that the projects do not disturb any neighbours on land, and they do not take up space, that could be used for something else. The disadvantages of having hydrogen production offshore are, nonetheless, it has never been done before, which entails several risks, it might be more expensive to develop a PtX project offshore than onshore, and a lot of synergies must align, if the purpose of such a project is to be connected to other countries, than just Denmark. If offshore projects were included in this report and analysis, it would have affected the results in several ways, as the expansion and development of the electricity grid and the hydrogen pipeline would have been bigger due to the larger distances to the existing grid and proposed pipeline. It is also most likely, that PtX projects developed offshore will have a larger capacity than projects developed on land, so more capacity would have to be included in the analysis or fewer projects.

The socio-economic analysis concludes that scenario 2 and 3 with a positive NPV are socioeconomically feasible. From the analysis, it is also found that the feasibility of the scenarios is highly dependent on the hydrogen price. The analysis suggests that for Denmark to be an exporter of hydrogen, the capacities and investments should follow scenarios 2 or 3 rather than scenario 1. This indicates that the higher the production and capacities of PtX, the more socioeconomically feasible it is for Denmark to be an exporter of hydrogen. In this report, the socio-economic results of Denmark exporting hydrogen are investigated. It can, however, be discussed if Denmark should even export hydrogen, even though it is economically feasible. If Denmark exports hydrogen and it is economically feasible, an advantage is, that the hydrogen is a revenue for Denmark. As most projects are developed by private developers, the revenue will, however, favour the developer, but the growth of the PtX business in Denmark has several advantages such as job creation, world-leading within the industry, and expanding existing infrastructure, which might lead to other revenues. A reason for Denmark being an exporter of hydrogen besides potential economic benefits, is the good wind resources, especially offshore. As the climate crisis is a worldwide problem and not only affects a couple of countries, it is beneficial for every country to contribute to accommodating the climate goals on a global level. It makes sense to exploit the local resources and to develop wind turbines, in places with the best wind resources, as well as it makes sense to develop PV projects in places with the best solar resources. As Denmark is a relatively small country it is also relatively limited how much the Danish emissions contribute to the greater picture of polluting the environment. On one hand, one can argue, that Denmark should focus on meeting its own climate goals first, but on the other hand, the Danish resources have the potential to contribute to other countries' climate goals and thereby contribute to the greater good of the world. Another factor to consider when determining if Denmark should be an exporter of hydrogen is the hydrogen market in Denmark and the offtake possibilities. It is relevant to investigate if there are companies in Denmark that would offtake some of the produced hydrogen.

As PtX projects play a crucial role in the future energy system, it is also necessary, that abundant RES projects are developed, the necessary infrastructure is in place, and the offtake side is ready to use the PtX fuels. A crucial part of a PtX project is the electricity from RES, and the energy yield from the RES is very location-dependent. An export of hydrogen cannot be realized if there is no consent for implementing an additional offshore wind turbine capacity to accommodate the higher electricity demand from the electrolyser. The export of hydrogen cannot happen if e.g. the hydrogen pipeline to Germany is not in place, and if it is not implemented in appropriate capacities to follow the demand. Not only does an export of hydrogen in 2045 require large investments in infrastructure, but it also requires that the planning and implementation of these infrastructure and other technologies run smoothly without too many delays. Some industries' processes might have to make changes to use PtX fuels, and this can also be time-consuming. It is most likely not possible, for all the timelines of the PtX processes to align, but it is important to accommodate this in the best possible manner by having good communication with all the stakeholders in the PtX value chain, to secure the security of supply of PtX fuels, and regulations must be implemented on a political level. For the planning and implementation to run smoothly the political environment in Denmark is crucial and if the Danish government is non-progressive towards transitioning the energy system towards RES it might be difficult to implement new renewable technologies and reach the climate goals.

10 Conclusion

This master thesis analyses the socio-economic feasibility of Denmark exporting hydrogen and potential regulatory challenges and means of action regarding the development of PtX in Denmark. PtX plays a crucial role in reaching national and global climate goals. To exploit the local resources of Denmark export of hydrogen produced from PtX is favourable due to the excellent wind resources and a relatively low demand for hydrogen in Denmark. Germany is especially an obvious offtaker of Danish-produced hydrogen, as they have a large demand in their industry, and a hydrogen infrastructure is planned to be developed between Denmark and Germany. Before PtX can reach its full potential proper regulation has to be in place. Some regulation is already made on an EU level, but this has to be implemented by the individual countries, which might be time-consuming, and thereby delay the development of PtX projects in Denmark.

The report analyses the socio-economic consequences of Denmark exporting hydrogen based on three different scenarios. To accommodate a hydrogen export the scenarios are modelled based on the IDA Climate Response 2045, where scenario 1 has an additional electrolyser capacity of 5 GW, 9.3 GW additional offshore wind capacity and an additional fixed hydrogen export of 30.75 TWh/year. Scenario 2 has an additional electrolyser capacity of 10 GW, 16.3 GW additional offshore wind capacity and an additional fixed hydrogen export of 54.3 TWh/year compared to the IDA Climate Response 2045. Scenario 3 has an additional electrolyser capacity of 15 GW, 22.9 GW additional offshore wind capacity and an additional fixed hydrogen export of 77.85 TWh/year compared to the IDA Climate Response 2045 report. The operation of the electrolyser is analysed to be running based on a 75% fixed hydrogen export value and CEEP. The exported hydrogen in the scenarios constitutes respectively 9%, 16% and 22% of the German hydrogen demand.

The result of the socio-economic analysis shows that of the three scenarios, scenarios 2 and 3 are socio-economic feasible with the given parameters of the analysis. To investigate when and if scenario 1 is socio-economic feasible, a sensitivity analysis is conducted on the electricity price, the hydrogen price, and the investment cost of the offshore wind turbines. The electricity price and the hydrogen price have been highlighted as some of the largest barriers to developing PtX projects, which is why these are included in the sensitivity analysis. The investment cost of the offshore wind turbines is included in the sensitivity analysis as this cost constitutes the largest share of the cost of the PtX projects in the socio-economic calculations. The sensitivity analysis finds, compared to the used parameters, that for scenario 1 to be socio-economic feasible, the electricity price must be reduced by 10%, the hydrogen price must increase by 10%, or the investment cost of the offshore wind turbines must be reduced by 10%. The three scenarios are socio-economic feasible with a hydrogen price of respectively 3.3 EUR/kg, 3 EUR/kg, and 2.7 EUR/kg for scenarios 1, 2, and 3.

The biggest challenges and means of action the interviewed stakeholders mentioned concerns mainly around: PtX is a new industry, tariffs, secure renewable electricity, offtake and the price of hydrogen, developing a hydrogen infrastructure, the business case, the hydrogen market is new and uncertain, regulation, alignment of all processes and general uncertainties. Especially proper regulation is requested, for the stakeholders to know how to navigate and which requirements to achieve. Another important aspect that is mentioned by several of the interviewed stakeholders is the development of a hydrogen pipeline and the associated tariff model design. A hydrogen pipeline constitutes the largest offtake possibility and is crucial if more hydrogen PtX projects should be developed. The development of hydrogen PtX projects in Denmark thereby depends on political support, the proper infrastructure to be in place for the entire value chain, and an offtaker of the hydrogen.

It is concluded, based on the analysis, that it is socio-economic feasible for Denmark to export hydrogen. The socio-economic consequence of the analysis does, however, highlight, that before the NPV is positive the PtX projects should be large-scale due to the relation between the cost per year, investments, and revenue.

As most of the existing regulation is on an EU level, a way to improve the regulatory framework is to implement EU regulations and further develop the framework. Regulations must be politically introduced to accommodate the development of PtX towards 2045.

11 References

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12 Appendix

12.1 Technology Investment Cost

Technology	Economic parameter	Value	Lifetime (years)	Source
Electrolyser 100 MW AEC	Specific investment (€/kW of total input(e))	300	32	[27]
	Fixed O&M (% of specific investment/year)	2		
Offshore wind turbine	Nominal investment (M€/MW)	1.68	30	[84]
	Fixed O&M (€/MW/year)	34,000		
	Variable O&M (€/MWh)	3.42		
Hydrogen storage Underground storage	Nominal investment (M€/MWh)	0.0015	100	[86]
	Fixed O&M (M€/MW/year	0.00003		
	Variable O&M (€/MWh)	0.000015		
Electricity distribution New developed areas, single line 100 - 500 kW	Investment cost (€/m)	36	40	[90]
	Fixed O&M (€/MW/year)	1321		
Hydrogen pipeline 140 bar, 250 - 500 MW	Investment cost (€/MW/m)	1.1	50	[90]
	Fixed O&M (€/km/year/MW)	0.20		

12.2 Revenue, Investment, and Yearly Cost of Scenarios

Revenue and investment of scenarios			
	Scenario 1	Scenario 2	Scenario 3
Revenue of scenario			
Hydrogen offtake price for 1 year (MEUR)	2,770	4,892	7,014
Export of electricity spot price 1 year (MEUR)	190	202	215
Total revenue for 1 year (MEUR)	2,960	5,094	7,229
One-time investment of scenario (scrap value included)			
Electrolyser (MEUR)	2,836	4,282	5,729
Offshore wind turbine (MEUR)	39,144	50,904	61,992
Hydrogen storage (MEUR)	703	1,062	1,423
Electricity distribution (MEUR)	0.496	0.992	1.488
Hydrogen pipelines (MEUR)	72	145	217
Total one-time investment (MEUR)	42,756	56,395	69,363
Cost per year			
Price of natural gas consumption per year (MEUR)	70	108	150
Import of electricity (MEUR/year)	713	879	1,098
Total cost per Year incl. O&M (MEUR)	2,001	2,586	3,208

O&M/year			
	Scenario 1	Scenario 2	Scenario 3
Electrolyser (MEUR)	57	86	115
Offshore wind turbines (MEUR)	1,148	1,493	1,818
Hydrogen storage (MEUR)	0.000022	0.000037	0.000052
Electricity distribution (MEUR)	12.9	19.6	26.2
Hydrogen pipes (MEUR)	0.12	0.42	0.89
Total O&M (MEUR)	1218	1599	1960

12.3 Excel Sheet: Economic Calculations

The Excel sheet with the socio-economic calculations is uploaded externally under the name "*Appendix 12.3 – Economic Calculations*".

12.4 Excel Sheet: Interview Matrix

The interview matrix containing relevant statements from interviews is uploaded externally under the name "*Appendix 12.4 – Interview Matrix*".

12.5 Excel Sheet: Comparison of Scenarios

The Excel sheet with a comparison table of the scenarios is uploaded externally under the name "*Appendix 12.5 - Final Scenarios*".

12.6 Excel Skeet: Fixed and CEEP operation

The Excel sheet with the analysis of the operation of the electrolyser based on a fixed hydrogen export demand and the inclusion of CEEP is uploaded externally under the name "*Appendix 12.6 – Fixed and CEEP*".

12.7 Excel Sheet: Scenarios 1, 2, and 3

The Excel sheets with the different scenarios are uploaded externally under the names "*Appendix 12.7 – Offshore Capacity Scenario 1*", "A*ppendix 12.7 – Offshore Capacity Scenario 2*", and "*Appendix 12.7 – Offshore Capacity Scenario 3*".