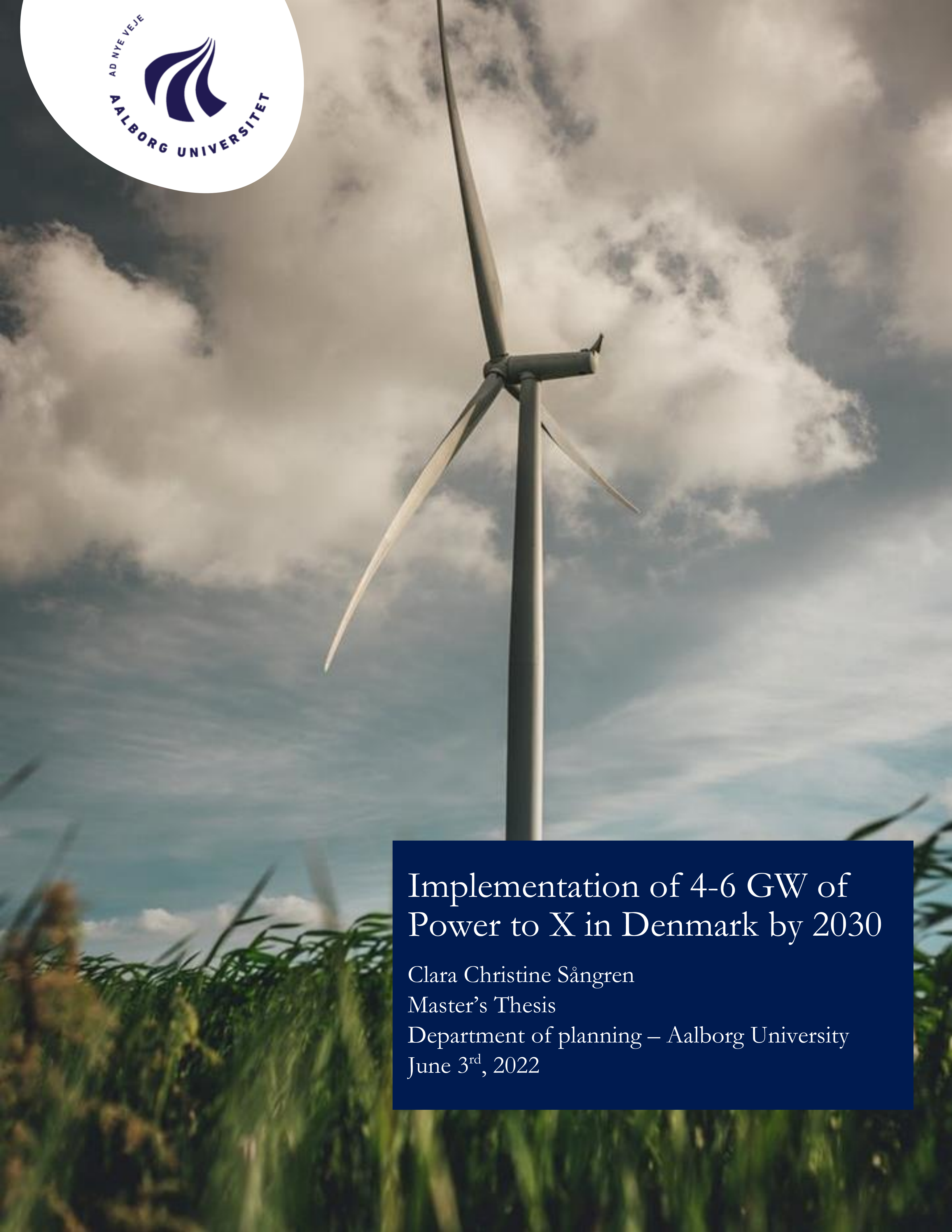

Implementation of 4-6 GW of Power to X in Denmark by 2030

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1. Abstract

For the Danish energy system to reach The aim of this master's thesis is to investigate the impacts of integrating 4-6 GW of Power-to-X (PtX) in the Danish energy system by 2030 and what initiatives are necessary for it to be implemented successfully.

To answer this question two analyses has been conducted.

The first analysis is an energy system analysis conducted in the energy system analysis tool EnergyPLAN. The concept of Smart energy system is used as a framework for conducting the analysis . PtX is therefore not only seen as a possible solution to decarbonize the transport sector, but also as a technology able to provide flexibility in an energy system increasing based on fluctuating sources. To analyse the impact of 4-6 GW of PtX 4 different scenarios are analysed. One scenario without any PtX production. One scenario with 4 GW and one with 6 GW reflect the political agreement's goal for PtX in 2030. And lastly, a scenario simulates the amount of PtX needed to reach the Danish climate goal of a 70% CO2 reduction by 2030.

It was found that implementing 4-6 GW of PtX requires a large amount of energy, more precisely an addition of 20-32 TWh RE/year, compared to a system without PtX. Meanwhile, by replacing oil in the transport sector, PtX can reduce the CO2 emission from the energy sectors by up to 24%. This, however, requires the system to be operated flexibly to ensure only use excess electricity from the fluctuating energy production.

The second analysis dives into how the implementation of PtX can be achieved. This is something that a number of actors have dealt with, the analysis is therefore based on previously published plans and proposals for strategies for the implementation of PtX. These plans are compared with the political agreement, which in addition to the target of 4-6 GW PtX also contains agreements on how the implementation is to be achieved. On the basis of this, an overview is drawn up of initiatives that the actors propose for the implementation. These initiatives are then discussed, in order to end with a recommendation of which initiatives are needed for a successful implementation of PtX.

2. Danish summary

Størstedelen af verdens energiforbrug dækkes i dag af fossile brændsler, dette er et problem eftersom afbrændingen af fossile brændsler er forbundet med udledningen af CO2 som er den primære menneskeforårsaget bidrag til klimaforandringer.

For at reducere udledningen og leve op til Danmarks klimamål om en 70% CO2 reduktion i 2030 og CO2 neutralitet i 2050 er der behov for en reduktion af udledningen i alle sektorer. Dette er imidlertid forbundet med udfordringer. Transportsektoren er især udfordrende, dette skyldes at særligt dele af skibs- og luftfarten har behov for drivmidler med høj energidensitet, hvilket endnu ikke kan dækkes gennem en direkte elektrificering. Der er derfor behov for andre alternativer til det nuværende forbrug af fossile brændsler. Et sådan alternativ er Power-to-X, som er navnet bag konceptet at producerer brændsler eller kemikalier baseret på elektricitet. Folketinget bakker op om at der er behov for PtX, et bredt flertal i folketinget vedtog således i marts 2022 en politisk aftale for at fremme implementeringen af PtX. Med denne aftale blev der bestemt et mål om at implementere 4-6 GW PtX i Danmark i 2030. Dette er et stort spring fra den nuværende situation, hvor der kun produceres e-brændsler på test-skala og elektrolyse kapaciteten endnu er begrænset. Desuden har PtX processen et stort behov for el, især elektrolyseanlæg som producerer brint er en meget energikrævende proces. For at understøtte dette behov og sikre en grøn produktion er der behov for en signifikant udbygning af vedvarende energi produktion. Udover at være en energikrævende proces har PtX imidlertid den fordel at teknologien kan driftes fleksibelt og dermed bidrage til en bedre udnyttelse af vedvarende energi produktion.

Fra en transport sektor som primært er dækket af fossile brændsler og dermed ikke har krævet en større sammentænkning med det resterende energisystem, vil transport sektoren med PtX blive forbundet til resten af energisystemet, eftersom alle sektorer i stigende grad forsynes med vedvarende energi.

Formålet med dette speciale er derfor at undersøge hvordan 4-6 GW PtX vil påvirke Danmarks energisystem i 2030 og yderligere hvilke virkemidler som bør prioriteres for en succesfuld implementering.

For at undersøge dette er der fortaget to analyser. Den første analyse er en energisystemsanalyse. For at lave en holistisk energisystemsanalyse og understøtte en smart sammenplanlægning på tværs af energisystem (kendt under termen Smart energi system) benyttes analyseværktøjet EnergyPLAN. I energisystemsanalysen vurderes det hvordan implementeringen at 4-6 GW elektrolyse påvirker energisystemet. Herunder hvor stor en kapacitet af vedvarende energi en sådan udbygning kræver, hvordan PtX skal driftes, hvordan systemomkostninger påvirkes og ikke mindst hvor stor en andel af det fossile brændsel som kan fortrænges og klimaeffekten heraf.

Resultaterne viser at implementeringen af PtX er forbundet med høje systemmæssige omkostninger, men ligeledes potentielt kan reducere CO2 udledningen fra transportsektoren betydeligt. Derudover ses det at energisystemet i langt højere grad kan udnytte vedvarende energi fra fluktuerende energikilder, hvilket viser den øgede fleksibilitet som PtX medfører.

Den anden analyse dykker ned i hvordan implementeringen af PtX kan opnås. Dette er noget som en række aktører har beskæftiget sig med, analysen tager derfor udgangspunkt i tidligere udgivet planer og forlag til strategier for implementeringen af PtX. Disse planer sammenholdes med den politiske aftale, som udover målsætningen om 4-6 GW PtX også indeholder aftaler om hvordan implementeringen skal opnås. På baggrund af dette opstilles en oversigt over initiativer som aktørerne forslår for implementeringen. Disse initiativer diskuteres herefter, for at ende ud med en anbefaling af hvilke initiativer der er behov for, for en succesfuld implementering af PtX.

3. Preface

This master's thesis is made as a completion of the Master of Science program in Sustainable Cities at Aalborg University Copenhagen.

I would like to thank my supervisor, Brian Vad Mathiesen, for valuable feedback and guidance throughout the project.

4. List of abbreviations

CO2: Carbon dioxid

E-fuel: Electrofuels

GHG: Greenhouse gas

PEM: Polymer electrolyte membrane

PtX: Power-to-X

PV: Photovoltaics

RE: Renewable energy

RES: Renewable energy sources

SES: Smart energy system

SOEC: Solid oxide electrolyser cell

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6. Introduction

6.1 The transition toward carbon neutrality in Denmark

Worldwide fossil fuels are still the primary source of energy supply. This is a problem as the use of fossil fuels is interconnected with the largest human-caused contribution to climate change (Skov et al. 2021; Ritchie, Roser, and Rosado 2020). To limit the temperature rising to 1,5 degrees, as decided on in the Paris agreement, phasing out fossil fuels is necessary (IPCC 2022). Under the Paris agreement, Denmark has submitted a legally binding climate law enacted by the Danish parliament in 2020. The climate law dictates that Denmark needs to reduce their carbon emission by 70% in 2030 compared to 1990. (Klima-, Energi- og Forsyningsministeriet 2020) The CO2 emissions in Denmark have been reduced by 34% since 1990. To reach the 70%-reduction goal, the same reduction needs to happen within the following 8 years. (The Danish Government's Climate partnership 2020)

To reach these goals, the dependency on fossil fuels in the energy system needs to be reduced and the energy demand needs to be covered by renewable energy. Denmark has great renewable energy sources. Especially wind is an important resource, this is both due to the proximity to the sea and the flat terrain, but also the fact that Denmark was a pioneer in developing wind power with the first onshore wind turbine being installed in the 1970s (Energistyrelsen 2011). In 2019[1] 35% of the Danish energy consumption was covered by renewable energy. Wind and solar energy covered 12% of the total energy production whereas the rest of the renewable energy was covered by bioenergy. This also means that the biggest share of the Danish energy demand is still covered by fossil fuels. (Energistyrelsen 2019)

While most sectors have reduced the demand, the transport sector has over the past years increased the use of fossil fuels. This is due to a growth in travel demand, leading to an increase in energy demand (Kany et al. 2022). Compared to 1990 the energy demand for transport has increased by 30% (Energistyrelsen 2019). In 1990 transport was accounting for 21% of the total GHG from Denmark, in 2019 the share had grown to 37%, due to both the general decrease in emissions and an increase in emissions from transport, see Figure 1. Road transport accounts for 67% and thereby the largest share of the emissions, while 31% derives from aviation and maritime transport (Kany et al. 2022). To meet the renewable energy goals, the transport sector needs a transition away from the use of fossil fuels.

[1] 2019 is used as reference as the demand in 2020 and 2021 have been influenced by COVID-19

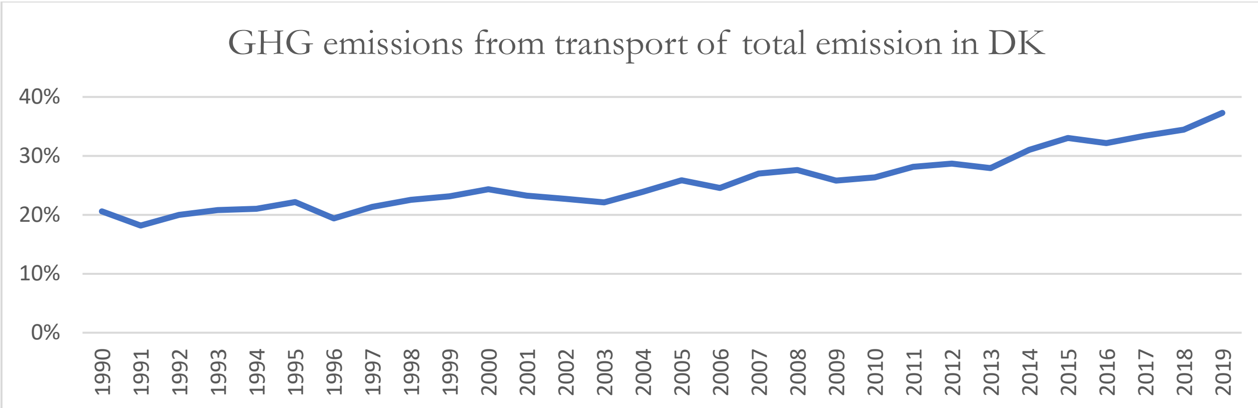


Figure 1 - The share of emission from the transport sector compared to the total emission of GHG in DK. The transport emission is consisting of data from the IPCC source categories 1.A.3, 1.D.1.a, and 1.D.1b. The total emission is the EEA category "Total emissions with international transport"

The largest energy demand in the transport sector is expected to be directly electrified, for instance, all the current fossil-fuelled passenger vehicles should be replaced with electric vehicles in the future (Lund, Mathiesen, et al. 2021; Dansk Energi 2020). This is the most efficient use of energy and is cheaper than current alternative technologies. It has been calculated that around 70% of electricity is used for propulsion in battery-based vehicles, while the loss in the process of producing and using hydrogen means that only 30% of the initial energy content is converted into propulsion in a hydrogen car.(Danish ministry of Climate, Energy and Utilities 2021) . However, one of the major problems in decarbonizing the transport sector is that the entire demand cannot be electrified, part of the demand must be supplied by liquid or gaseous fuels. (Kany et al. 2022; Lund, Mathiesen, et al. 2021; DTU et al. 2021)

6.2 Power to X as an alternative to fossil fuels and the role of biofuels

To reach carbon neutrality and meet the climate goals, carbon-neutral fuels need to supply the part of the demand which cannot be electrified. Power-to-X, PtX, and biofuels are solutions to this. While biomass is a good substitute for fossil fuels, it is a resource in high demand and has limitations in availability. There are different perceptions on how much biomass is available, according to the Danish Council on Climate Change (2018) the limit for sustainable use of biomass is 100 EJ/year globally which corresponds to 10 GJ/capita globally (Klimarådet 2018). In Denmark 29 GJ of biomass is used per capita (2020 data)(Lund, Mathiesen, et al. 2021), exceeding the globally assessed sustainable use times three.

Because of the high demand, biomass needs to be used sustainably and planned for considering the nexus between the need for biomass as food supply, building materials, fuels, etc. A consequence of a non-sustainable use of biomass, could be a reorganisation of agricultural land from food production to be used for energy crops, which is not a desired development. (Leck et al. 2015) Biomass should therefore not be used when alternatives are present. The usage of biomass to produce fuels for transport should therefore be kept at a minimum.

PtX is as mentioned another solution to produce fossil-free fuels for transport. PtX is the name behind the concept of converting electricity to fuels or chemicals. Using electrolysers water can be split into hydrogen and oxygen. Hydrogen can be used directly in heavy transport, but it can also be used to produce other fuels or chemicals. For instance, it can produce ammonia through a synthesis process with nitrogen. Likewise, carbon can be added to the hydrogen to produce methanol, kerosene, and other carbon-based fuels. Besides being used for the transport sector, hydrogen and the fuel and chemicals produced from it can be used in industry and agriculture. The largest use of hydrogen is today used for producing ammonia as fertilizer. (Dansk Energi 2020).

To produce the different fuels several technologies are required. The readiness level of these technologies varies, however the the key technologies to PtX are well developed. To define the readiness of a technology the so-called technology readiness level, TRL, can be used. TRL is a scale from 1-9 where 1 is defined as *"Basic principles observed"* (European commission 2017, 1)and is the definition for the least developed technologies and 9 the most developed technology, described as *"actual system proven in operational environment"*(European commission 2017, 3).

The first step to producing e-fuels is to produce hydrogen through a hydrogen-electrolyser. The three most promising types are Alkaline, Polymer electrolyte membrane (PEM), and Solid oxide electrolyser cell (SOEC). Alkaline and PEM are both mature technologies with a TRL of 8-9. SOEC has a TRL of 6-7 meaning that it is less developed but has been demonstrated in a relevant environment. Even though Alkaline and PEM have a high TRL, the efficiencies are rather low, and the cost is high. SOEC is expected to reach higher efficiencies when it gets further developed. The primary focus for further development of the electrolyser technologies is to decrease the cost. (European commission 2017; Aalborg University et al. 2021)

For the fuels based on carbon, there needs to be a carbon source. This requires carbon capture. Carbon capture is well-developed and has a TRL on 9. (Aalborg University et al. 2021)

To produce fuels from carbon and hydrogen further requires chemical synthesis. The production of methanol has a TRL on 9 (DTU et al. 2021), however, to produce jet fuels/e-kerosene this needs to go through a further process which has a TRL on 5-6. To produce jet fuel from methanol therefore still requires development and testing. Alternatively, jet fuels can be produced through Fischer-Tropsch synthesis (DTU et al. 2021; Aalborg University et al. 2021)

The production of ammonia does not need a carbon source, instead, it can be produced by combining nitrogen with hydrogen. This is done through a process called Haber-Bosch, which is widely used today (TRL 9), however, the process currently uses hydrogen produced with fossil fuels. (Aalborg University et al. 2021)

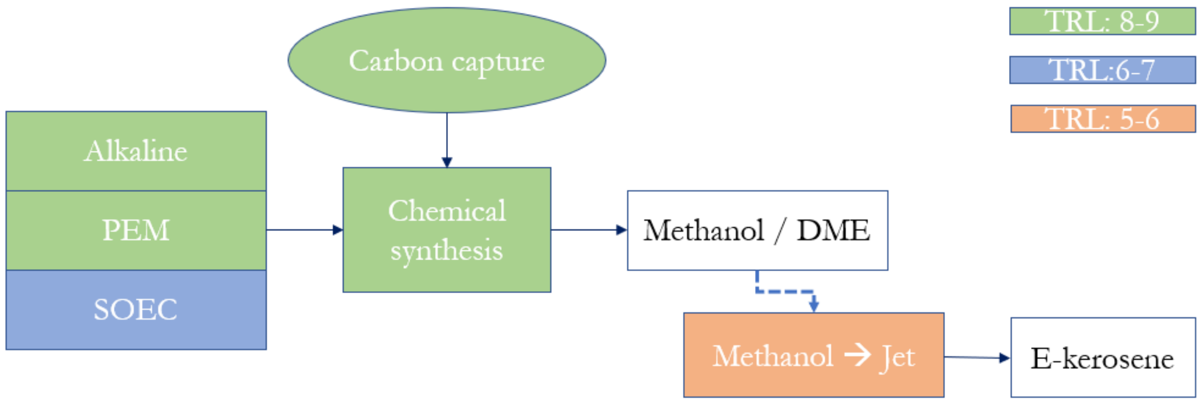


Figure 2 - Overview of TRL of some of the key processes in PtX to produce carbon-containing fuels. The TRL are based on data from Aalborg University et al. (2021) and the figure is inspired by (Skov and Mathiesen 2017)

6.3 From planning in silos to a smart energy system

Traditionally the energy system has been seen and planned for divided based on sectors. Ensuring the energy demand of the transport sector to be covered in all hours in an energy system based solely on fossil fuel is rather simple, from an energy planner's view, as fossil fuels have the advantages of being easy to store, which provides flexibility within the resource. However, when shifting away from fossil fuels, to fluctuating RE sources, this flexibility of storage will be lost, as electricity is expensive and inefficient to store (Lund et al. 2016). Reaching a 100% renewable energy system therefore requires a rethinking of the current energy system away from the dividing the system into silos toward holistic planning of the energy system. Meaning that the energy system should be planned across sectors and storing options with the aim of integrating synergies between the sectors to cover the demand during all hours. (Mathiesen, Lund, et al. 2015; Ridjan 2015) This concept is known under the term Smart energy systems and is further elaborated upon in section ***Error! Reference source not found. Error! Reference source not found.***.

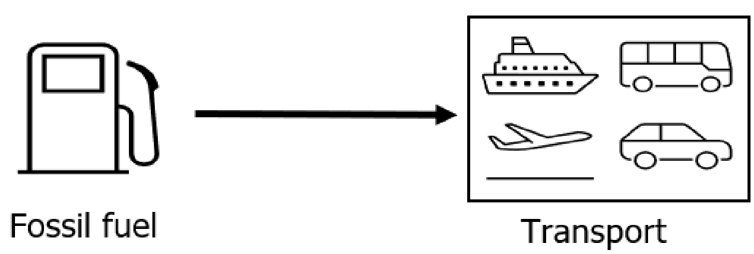


Figure 3 - Conventional way of looking at the transport sector

6.3.1. The transport sector as a part of a Smart energy system:

When the transport sector is planned for as a part of a smart energy system, the focus will not only be on how to cover the demand in the transport sector hour by hour but on how to secure the supply of the total demand in the system in all hours. As shown in *Figure 4*, PtX interlinks the transport sector with the rest of the energy system. In an energy system running on 100% renewable energy this mean that the energy produced by a renewable source (e.g. wind power) needs to be shared to cover all demand in the system. Whereas the flexibility in the conventional energy system were within the energy source, the flexibility now needs to be provided by the conversion and storing of energy. PtX has the ability of converting electricity into fuels which unlike electricity can be stored cheap and efficiently, providing flexibility to the system. Supplying the transport sector is therefore not solely dependent on the hourly production but has a precaution in the storage (Ridjan 2015). In hours with more RE production than demand, the electricity can be used in the electrolyser to produce hydrogen, which can be upgraded through fuel synthesis to e-fuels.

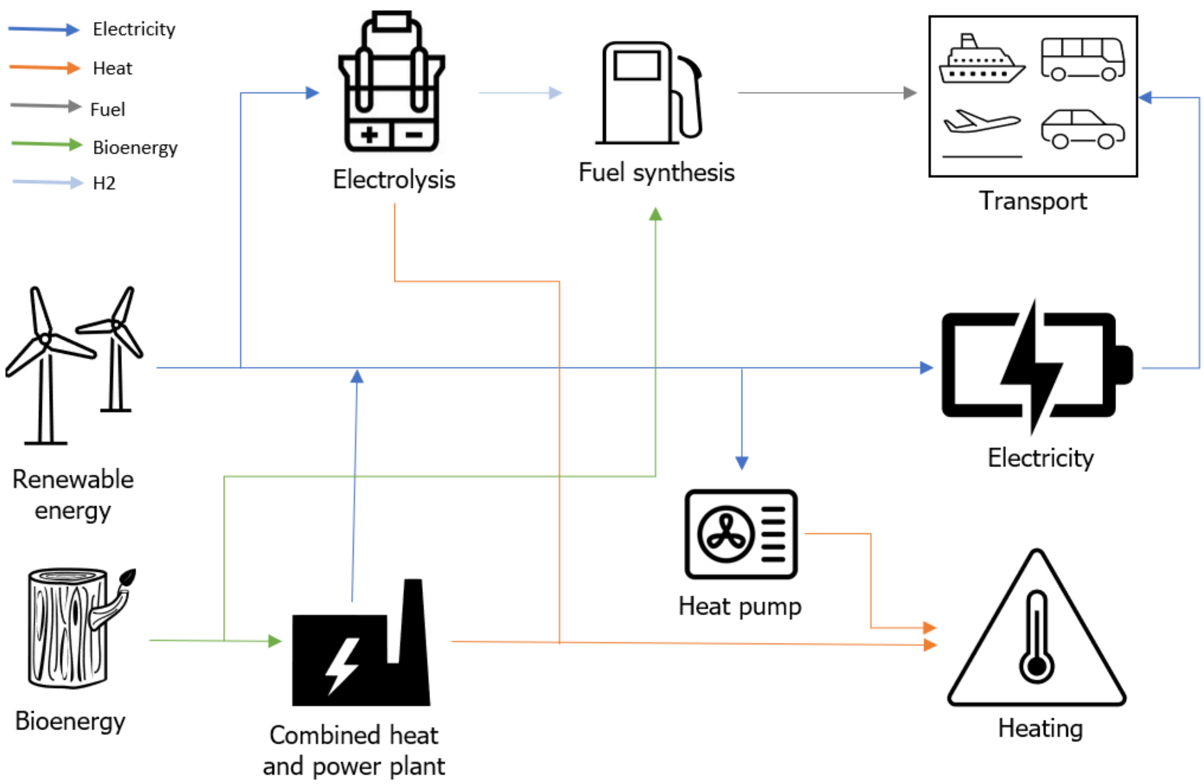


Figure 4 - The new way of looking at the transport sector as a part of a smart energy system (simplified energy system)

6.4 The Danish PtX strategy

In December 2021 the Danish government published a proposal for the future development of PtX design as a roadmap. The roadmap suggested a goal of 4-6 GW in 2030, along with different initiatives to reach it. In March 2022, a political agreement was formed based on the roadmap enacting the aim of 4-6 GW of PtX. This is further elaborated upon in section *10.1 The political agreement to develop and promote PtX*.

Today PtX is not implemented in large scale in Denmark, and there is yet no production of e-fuels on commercial scale (Hydrogen Denmark 2020). It is therefore a ambitious plan going from solely having small scale test plants to scale up the production to 4-6 GW in 8 years.

The step towards implementing 4-6 GW of PtX will require a significant deployment of RES as producing hydrogen through electrolysis is a very energy-demanding process. To cover this demand and ensure a green production, there is a need for increasing the RE production. As previous mention PtX can however provide flexibility to the system and increase utilization of RE. It is therefore interesting to investigate the impact of the implementation of PtX in the energy system.

Based on reactions from different stakeholders, it seems like the reaction towards the goal of 4-6 GW primarily has been positive. Some actors do however express a concern regarding whether the deployment of RE will happen fast enough to cover the energy demand from 4-6 GW of PtX and express a need for more concrete plans to support the development of PtX (Capion and Sørensen 2022; Klimarådet 2022; Brintbranchen 2022).

7. Research question

With the introduction of a technology which has yet only not been implementing in large scale in the Danish energy system, it is interesting to invest how an ambitious and fast deployment will influence the energy system and what initiatives are needed in order to implement it.

This thesis therefore aims to answer the following research question:

What impact will 4-6 GW of PtX have on the Danish energy system and what initiatives are necessary for it to be implemented successfully?

8. Methodological framework

8.1 How do we model the complex reality?

When conducting the energy system analysis, the system is simulated in the energy system simulation tool EnergyPLAN. Ved at gøre dette modeller vi virkeligheden for at kunne xxx. Ifølge Latour vil dette imiderltid også medføre en reduktion af vide og kompleksitet.

Whereas (Latour 1999) described how a jungle was reduced from something complex to being explained and examined based on samples, photographs, etc., the Danish energy system can in this project be considered the jungle. To analyze an energy system in energyPLAN, it needs to be reduced from a complex system to a numeric value. This is necessary to get results, however, it is also important to understand the knowledge which is lost in the process. Some of the simplifications or reductions of complexity which is made to analyse the system are mentioned below.

Examples of knowledge objects used in energy to conceptualize reality:

The transmission lines: In EnergyPLAN it is possible to define the size/capacity of the transmission grid exporting electricity. However, in the model this transmission capacity can be used in all hours. I reality, this is not the case. For instance: In hours where there are a lot of wind and energy production, in Western Jutland, it is often also the case in Northern Germany. The transmission capacity can only be used if there is a receiver wanting the power. Further internal grids and potential bottlenecks are not considered, as there is not geographical attributes connected to the production or consumption in the model.

Technical optimal system: Energy plan can be operated as a technical optimal system, this means that the system knows when there will be excess power production and can utilize this. In real life we do not know the wind patterne in details until close to the production hour, it is therefore not possible to optimize the as well as in EnergyPLAN, where the wind- and solar power production is simplified into a distribution.

CEEP: The critical excess energy production is a theoretical value, as the system I real life would need to either export or downregulate.

8.2 Methodology:

The methodology will be explained for the two analyses. The first analysis is analysing what impact it will have on the Danish energy system in 2030 to implement 4-6 GW of electrolysis. The second analysis is looking into how 4-6 GW of electrolyser can be integrated analysing the political framework and roadmap made by different experts and actors within the sector.

8.2.1. Energy system analysis

To analyse the impact an increase in PtX will entail on the Danish energy system, it is analysed and compared how 0 GW, 1,12 GW, 4 GW, and 6 GW of PtX will influence the Danish energy system in 2030. One scenario without any PtX production. Two scenarios consisting of 4 and 6 GW of PtX, reflect the government's PtX strategy. And lastly, a scenario of 1,2 GW, to simulate the amount of PtX which, by IDA2030, is assessed to be needed to reach the Danish goal of a 70% reduction

The different scenarios are run through the energy system analysis tool EnergyPLAN. The modelling tool EnergyPLAN analyses the energy system holistically across the different energy-consuming sectors. The tool calculates the hourly balances in the different sectors and storage, with a focus on how the energy can be converted optimally between the sectors and storage possibilities. (kilde) EnergyPLAN was decided on as the modelling tool, as the analysis seeks to (1) include all energy-consuming sectors when assessing the influence of PtX. This is based on the smart energy system approach (elaborated upon in xx). (2) to simulate the energy system on a national scale for Denmark. (3) To use excess electricity which requires an hourly overview of energy demand and production.

When using EnergyPLAN, technical and market simulation strategies are available. The market simulation is working similarly to the NordPOOL market design, focusing on short-term prices. In a system with a great amount of dispatchable plants, the regulation of production depending on prices is a good way to regulate how the plant shall operate the production. However, in a system with high dependence on fluctuating sources of energy, the system needs to prioritize using this energy when it is available. When using the technical simulation, the tool aims to reduce excess electricity production and production in condensing power plants, implementing more wind and solar energy into the system. Table xx from xx provides an overview of the differences between the two simulation options. It was tested how the results differ depending on the simulation. The market simulation results in higher fuel demand and CO2 emissions, as it is worse at integrating the fluctuations from the RES. The higher fuel demand further leads to a more expensive cost of the system.

Based on this test and due to the focus on supplying the PtX with RES of energy (not including biomass) in hours with excess electricity production, while reducing the CO2 emissions, the technical simulation strategy is used as a simulation for this project.

Component	Input	Technical simulation	Market-economic simulation
Electrolysers	Capacity (electric) Efficiency Storage capacity (Demand is defined by hydrogen for transport, industry micro CHP as well as various demands for electrofuels)	Hydrogen production is determined by hydrogen demand for transport, industry, micro CHP and electrofuels etc. Hydrogen storage is used in order to relocate electricity consumption with the aim of decreasing excess electricity production and the quantity of condensing power in the overall system.	Hydrogen production is determined by hydrogen demand for transport, industry, micro CHP and for electrofuels etc. Hydrogen storage is used in order to achieve lowest market prices of the electricity consumed by electrolysers.

Figure 5 – from the energyPLAN (Lund, Thellufsen, et al. 2021)

In EnergyPLAN the link between the modelled system and the outside world consists of one transmission line with an entered capacity. EnergyPLAN cannot assess if the neighbouring country needs energy in the hours where there is excess electricity. The max import/export is therefore only limited by the capacity of the transmission line (Lund et al., 2019, s. 89). This is not corresponding with reality, as there will be times when the neighbouring countries have excess electricity in the same hours as Denmark. For instance, often when there are large shares of wind power in the Danish system the same tendency will be present in the northern part of Germany, which means that both places want to export electricity in the same hours, creating bottlenecks in the system.

This analysis aims to find how much RE there is needed in Denmark to supply the demand for electricity in a system with an increasing amount of PtX. The system is therefore modelled as a closed system without any capacity on the transmission line in the model, however, the theoretical value CEEP (critical excess electricity production), indicates how much export, or down-regulation, the system needs to be balanced.

Since the energy system is analysed considering the energy system holistically, the analysis is based on the existing model from IDA climate response 2030, IDA2030, with data for the energy-consuming sectors (excluding agriculture, LULUCF, and industrial processes). This includes supply and demand, cost, the lifetime of the technologies, efficiencies, etc.
IDA climate response is a plan, published in 2020, with initiatives for reducing greenhouse gas emissions by 70% by 2030. The investment cost for the technologies used for PtX can be found in appx. xx. All costs in the model are based on the IDA2030 and the interest rate is set to be 3%.

As the system is analysed holistically the result are dependent on the energy system. In a different energy system, the result would therefore differ. As the future is uncertain, any methodology, trying to forecast it, is associated with assumptions that can be debated. However, as the 2030 goal is to have reduced carbon emissions by 70%, IDA2030 is a reliable forecast of how the future energy system will potentially be.

8.2.2. Methodology in the second analysis

The second analysis is conducted as a document analysis, analysing and comparing 5 different roadmaps. (Bowen 2009) This approached is used to obtain an understanding of the different actors assessment of needed initiatives. The roadmaps are conducted by different actors, and can be consideres experts within the field, however the actors are also representing different interests. This should be considered when analysing the roadmaps.

Inspired by Hvelplund and Lund (1998), the second analysis seeks to find out how the regulation can support the process of moving from the current situation where the primary propellant for transport is fossil fuels, towards a green transition. In the current situation, fossil fuels are from a business perspective more attractive than alternative green fuels. From a societal perspective, there is however a need to decarbonize the transport sector, as stated in the introduction. To transition from the current situation to a situation favouring fossil-free fuels, there is a need for public regulation to construct a market economy, making what is best from the societal perspective also becomes the best solution for the business economy, to drive the development in the desired direction.
(Hvelplund and Lund 1998)

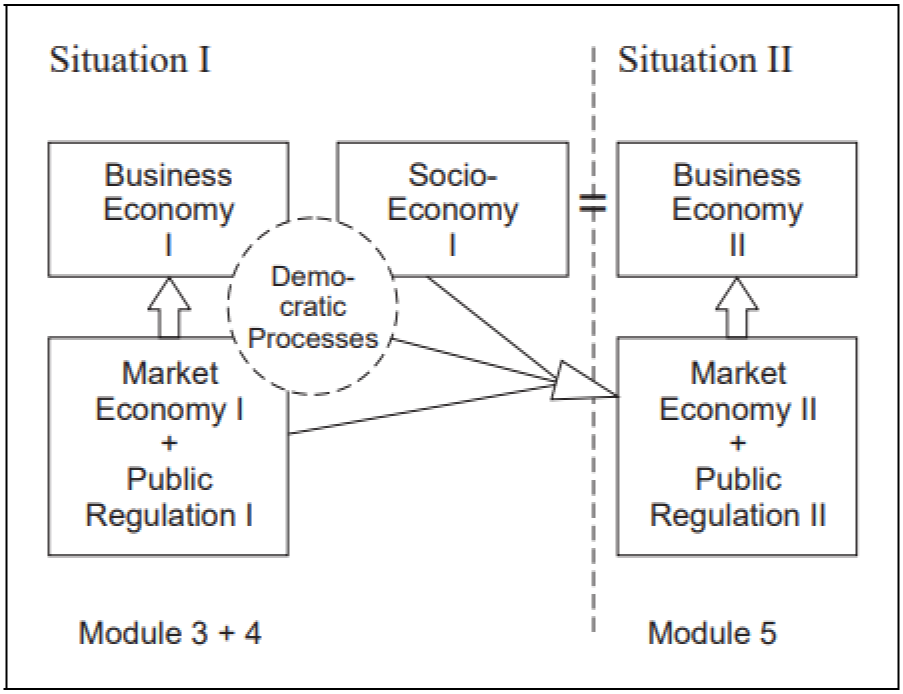


Figure 6 - The relationship between socio-economy, business economy and public regulation (Hvelplund and Lund 1998)

9. How will the energy system be affected by 4-6 GW of electrolyser?

Fulfilling the goal of the new political agreement of implementing 4-6 GW of PtX by 2030 will entail changes in the Danish energy system. As previous mentioned PtX is an energy demanding process and will therefore require an increase in energy production. Further the technology will connect the transport sector to the remaining energy system, whereas it has previous been seen more as a separate sector. To understand what impact this will have on the energy system, the implementation of 4-6 GW PtX in the Danish energy system by 2030 has been analysed through an energy system analysis.

The increasing capacity of PtX are to be used to cover the transport demand. Further it has to be operated based on the smart energy system concept. The analysis will therefore first investigate the demand for PtX in the transport sector, to assess where and how big demand the different transport modes have for e-fuels. Thereafter, it is analysed how to secure that the PtX has a positive effect in a smart energy system approach, adding flexibility and not increasing the demand for fossil fuels or biomass.

9.1 The demand for PtX in 2030

To analyse how 4-6 GW of PtX will influence the Danish energy system, it is essential to know what the end fuel should be used for. As mention *in 6.2 Power to X as an alternative to fossil fuels and the role of biofuels,* it is possible to produce multiple different fuel outputs from hydrogen. These end fuels can be used for different purposes. When analysing how PtX will influence the energy system it is essential to map the need for the different electrofuels as it will determine the demand.

When analysing the Danish energy system for 2030, the data used in the energy system analysis is, as mentioned in the methodology, based on IDA2030. However, the energy demand for transport in the data from IDA2030 is only covering the national transport while the energy demand linked to Denmark's contribution to international transport is not taken into account. This is done accordingly to the Kyoto and UNFCCC obligations, as it is established that only the emissions correlated with activities directly linked to a country are to be calculated (UN 2014). PtX however, plays an important role in decarbonizing long-distance transport which therefore primarily will be international transport, and not accounted for in the national totals. Instead of using the data from IDA2030 for the transport demand, Denmark's transport demand including the contribution to international transport is included in this analysis, as the biggest demand for PtX is found there. In Kany et al.'s (2022) strategy for decarbonizing the transport sector, Denmark's fuel demand for the transport sector in 2030, including the international transport, is estimated. This analysis will use these estimates as the demand. Table 7*Table 7* shows the fuel demand excluding the need for electricity for transport. **Error! Reference source not found.**(The raw data from Kany et al (2022) can be found in *14Appendix 1: A forecast of Denmark's energy consumption for transport incl. International transport in 2030*)

Fuels	Total demand in 2030 (TWh)	Biofuels in 2030 (TWh)	Fossil fuels in 2030 (TWh)
Jet fuel	13,3	0	13,3
Diesel/DME	24,1	1,4	22,7
Petrol/methanol	14,4	0,6	13,8
total	51,7	1,9	49,8

Table 7 – forecast of Denmark fuel demand for transport 2030 (Kany et al. 2022)

Based on the forecasted demand for 2030, the demand for PtX has been calculated. To assess the demand for PtX, the following assumptions are made based on current tendencies and expectations for future development.

1) The fuel demand from all passenger cars will be possible to electrify. (Lund, Mathiesen, et al. 2021; Kany et al. 2022; Energistyrelsen 2021)
2) 80% of heavy-duty road transport will be electrically driven. Leaving 20% of the demand to be covered by electrofuels. There are many different perceptions of what propellant heavy road transport will be using in the future, from fully electric driven, to driving on hydrogen or e-fuel. The 20% is used as it is the same as used in IDA2030 to achieve the 70% reduction. (Lund et al. 2020)
3) For maritime transport and aviation, all fuel demand, except the part covered by biofuel, is set as potentials for electrofuels to cover. This is a simplification, as some actors suggest that a larger share of the transport can be converted to be directly electrified, primarily ferries and in long term short-haul aviation. (Dansk Energi 2020; Aalborg University et al. 2021)
4) As previously mentioned, biomass is a limited resource. In the data for Denmark's energy demand for transport in 2030, biofuels are contributing to covering 1,9 TWh of the transport demand. (*Table 7 –)* Because of the limitation in availability this amount is kept stable.
5) The technical conversion speed is not taken into consideration. The fuel which can be replaced by electrofuels in Denmark in 2030 should therefore be expected to be lower than the potential found here, but to eventually reach this potential. As illustrated in Figure 1*Figure 8* especially the maritime transport is expected to be using fossil fuels as the propellant for a long while.

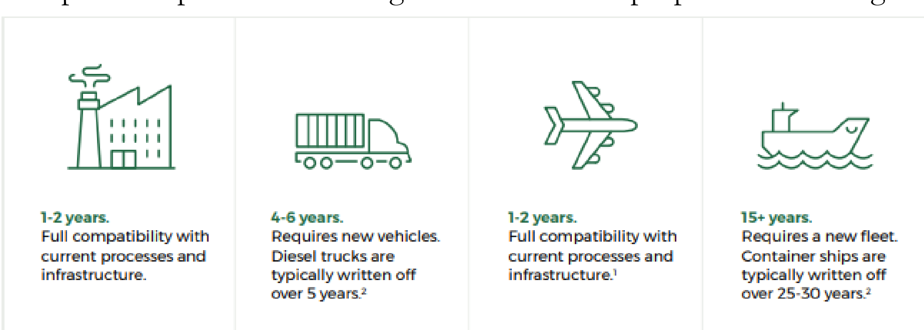


Figure 8 the technical conversion speed (Dansk Energi 2020)

6) Likewise, TRL is not taken into consideration. Power-to-jet fuel has a TRL on 5-6, and some actors do not expect it to be mature before 2030.

Based on these assumptions the following demand for PtX has been found for the Danish energy system in 2030.

PtX-demand by mode of transport	Fuel demand (TWh)
Aviation	13,3
Maritime transport	6,5
Heavy-duty transport (20%)	2,72
Total	22,52

Figure 9 – The demand for e-fuel 2030 – based on data from (Kany et al. 2022)

The different modes of transport can however not be supplied with the same types of e-fuels. As mentioned in xx, hydrogen can be used to produce various fuels with different applications. For heavy-duty transport either hydrogen, methanol, or DME can be used as fuels. The shipping can be supplied by methanol and ammonia and the aviation by E-kerosene. There are different conceptions of which the e-fuels will be used in the future. As there are several advantages and disadvantages of the different fuel types. This is not a discussion this analysis will dive into. Instead, respectively methanol and ammonia will be distributed to cover 50% each of the demand for e-fuels shipping, and methanol and DME for heavy-duty transport. While the aviation will be supplied with e-kerosene as e-fuel.

If the future development causes the demand to change, for instance, some actors foresee all trucks to be solely electric-driven and therefore don't need e-fuels, the production of electrofuels should be redirected to cover other demands or be exported. Methanol can for instance either be used in maritime transport or converted into e-kerosene and used for aviation (Dansk Energi 2020). If the electrofuels are exported, the fuels will still decrease the use of fossil fuels and reduce the GHG emissions, just in other places than Denmark, which is trivial from a climate perspective. Therefore, the exact use of the electrofuels is not of great importance for the results.

9.2 PtX as a source of flexibility

As previously introduced, this thesis investigates PtX as a part of a smart energy system, this means that when simulating the system, it is not only about how to meet the electricity demand of the PtX in all hours but also how to create the flexibility to help balance production and consumption in the energy system. Denmark has great wind resources, especially offshore there is a large potential for deploying the energy production. The added electricity demand for the PtX production is therefore expected primarily to be supplied by offshore wind energy. To create flexibility the electrolysers, therefore, need to be operated according to variations in wind patterns, to utilize the electricity production. This means that the full capacity of the electrolysers will not be used in all hours, as a constant operation does not favour the fluctuation of wind energy. Instead, there is a need for flexible operation of the PtX, to adapt to the energy balance in the system (Mathiesen, Ridjan, et al. 2015).

This flexible way of operating is illustrated in the figures below. The first scenario shows the system when there is more electricity production than demand. In this system, the storage of electrofuels will increase. In the second illustration, the energy system is illustrated when the RE supply is low.

In this scenario, all RE needs to be used to cover the electricity demand. The transport demand, therefore, needs to be covered by the stored fuels. The system will have more sources of flexibility, for instance in the heating sector where the heat, can be produced by heat pumps and stored when there is excess electricity, and then used when there is only enough electricity to cover the traditional electricity demand. (The illustration is inspired by Neves and Mathisen 2015, where heat pumps and storage are used as an example).

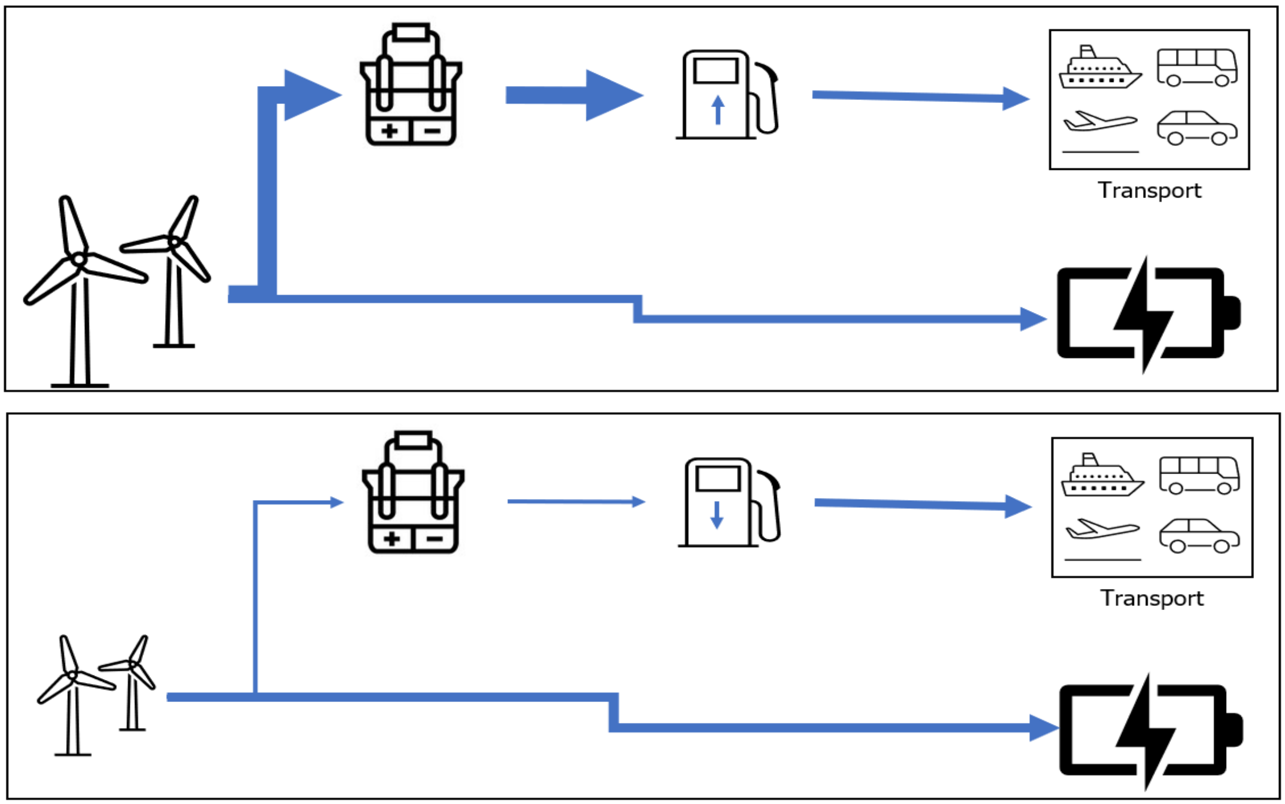


Figure 10 – PtX providing flexibility to the energy system

9.3 The framework for the energy system analysis

As mentioned, an energy system analysis is carried out to obtain knowledge about the impact of PtX in the energy system. Four different scenarios will be analysed, variating in the amount of PtX. In order to conduct the energy system analysis and ensure comparability between the scenarios, a framework for the analysis has been designed. This framework builds on the knowledge presented about operating PtX flexible and the demand for e-fuel in the transport sector. The following will go through the framework used for the energy system analysis.

9.3.1. Fuel demand

To ensure comparability between the different scenarios, the same fuel demand, being 22,5 TWh/year is covered in all scenarios. The demand is divided into the different sectors based on the distribution shown in *Table 7*. The remaining transport demand is expected to be covered by direct electrification. When the PtX capacity is increased, increasing the production of electrofuel, the consumption of fossil fuels is decreased, to keep the fuel demand for transport stable. In reality part of the fuel production might be exported, however, in EnergyPLAN the system is simulated on a national scale, therefore the full production of electrofuel replaces fossil fuels for transport in the system, to measure the effects on prices, CO2 emissions, etc.

The CO2 based e-fuels (methanol, e-kerosene, etc.) with the use of CO2 recycling, using emission from the use of biomass in other sectors, and without any direct use of biomass

9.3.2. Cost of infrastructure

The cost for the transport infrastructure and vehicles are the same for all scenarios. However, cost is added for fuels and investments in technologies according to changes in the amount of PtX.

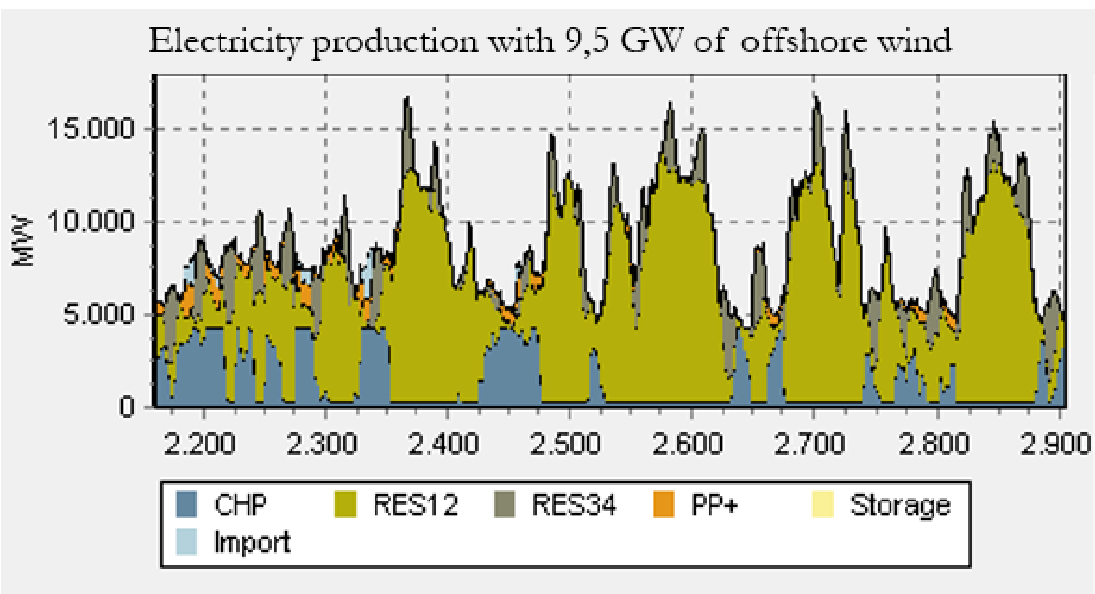
9.3.3. Storage

The electrolyser can integrate fluctuating energy, because of the possibility to store energy as fuels. To operate the PtX according to the wind production patterns a storage capacity big enough to store the electrofuels when it is required is needed. In the model, the storage capacity is increased along with the increase in PtX demand.

9.3.4. CEEP and RES

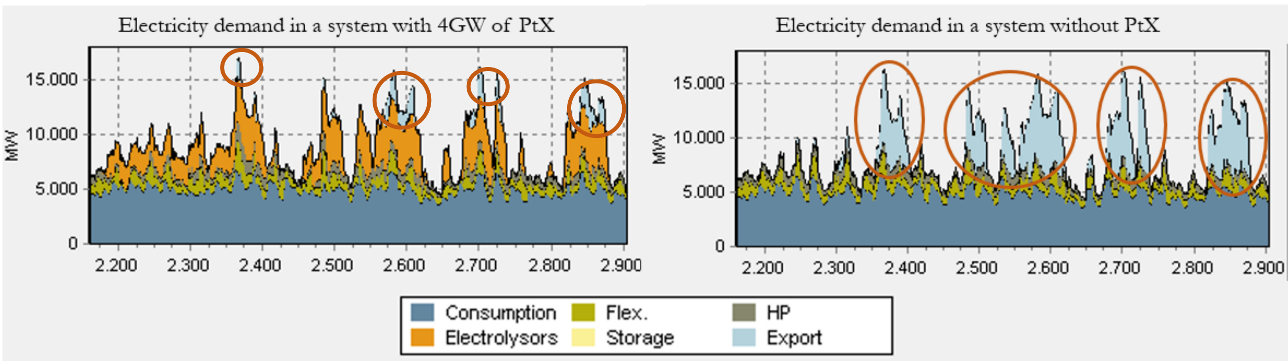
PtX has a great ability to integrate RE. This becomes clear when measuring the theoretical value of "Critical Excess Electricity Production", CEEP. CEEP is the measure of the yearly amount of electricity production the system cannot use. When electrolysers are added to the system the CEEP decreases significantly.

If we look at the Danish energy system for 2030 without any electrolyser and an offshore wind capacity of 9,5 GW. The production will look like Graph 11. (Here with the month of March used as an example):



Graph 11 – Grapig output from EnergyPLAN – May in 2030

The peaks show the great fluctuations in the productions. When the energy system cannot adjust to the peaks the electricity will either need to be exported or downregulated to balance the system. When there is a suitable amount of flexible electrolyser capacity the system will be able to utilize the production in almost all hours. The graphs below (*Graphs 12)* shows the difference between the system with and without PtX. In the system without PtX (graph to the right) there are large parts of the electricity production which cannot be used (marked with orange circles). Whereas the in the system with PtX almost all production can be utilized (graph to the left).



Graphs 12 – graphic outputs from EnergyPLAN

PtX is a process with large energy demand. To meet this demand the offshore wind capacities are adjusted, between the scenarios. The capacities of solar PVs and onshore wind turbines are fixed. The amount of offshore wind added to the system is defined by the CEEP to ensure comparability between the scenarios. *Figure 13* shows the different scenarios' ability to integrate RE. The dotted line shows the fixed CEEP. The place where the curves cross the dotted line is the amount of RE in the scenarios.

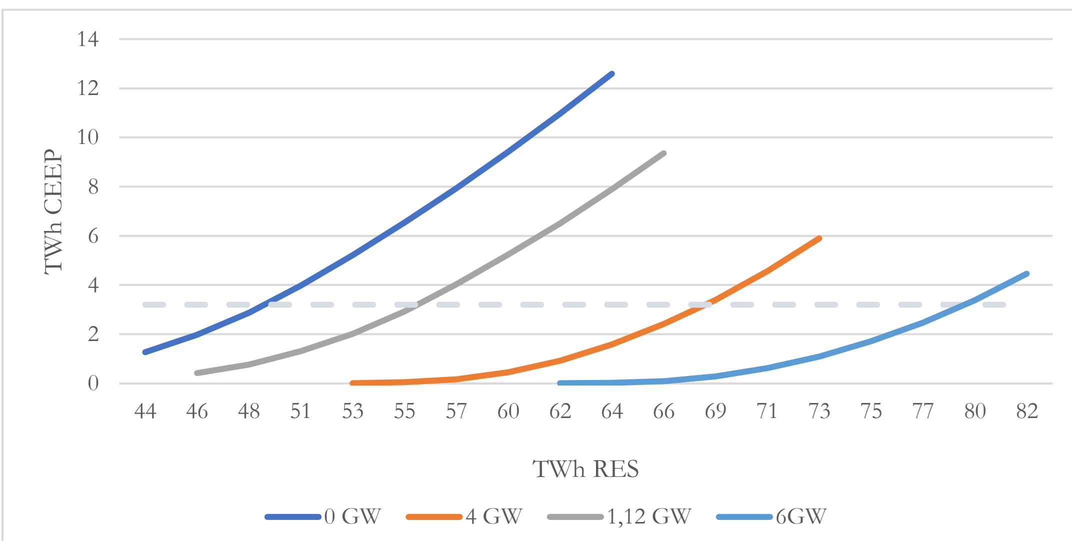


Figure 13 – The correlation between RE and CEEP in the scenarios

9.3.1. Flexible operation

A Danish and German case study from 2015 (Mathiesen, Ridjan, et al. 2015) found that in Denmark a yearly average operation of 50-60% of the full capacity of the electrolyser, gives the best options for integrating wind power without increasing the use of other plants. The energy system analysis takes this into account and has a maximum utilization of 60% of the electrolyzer capacity in all scenarios. It has been tested how the system reacts when the utilization is above the 60%, here with an operation of 77%. The CEEP is kept stable, introduction additional offshore wind to cover the increase in energy demand from increasing the operational time of the PtX. This shows an increase in carbon emission, thus a reduction in the use of fossil fuels for transport. This result is due to the electrolyser being forced to operate in hours without RE to cover the demand. The system, therefore, increases the use of power plants which are partly fuelled by natural gas, increasing the CO2 emission. Further, the use of biomass is increased, which as previously explained is not desirable. (the results can be found in appendix 7)

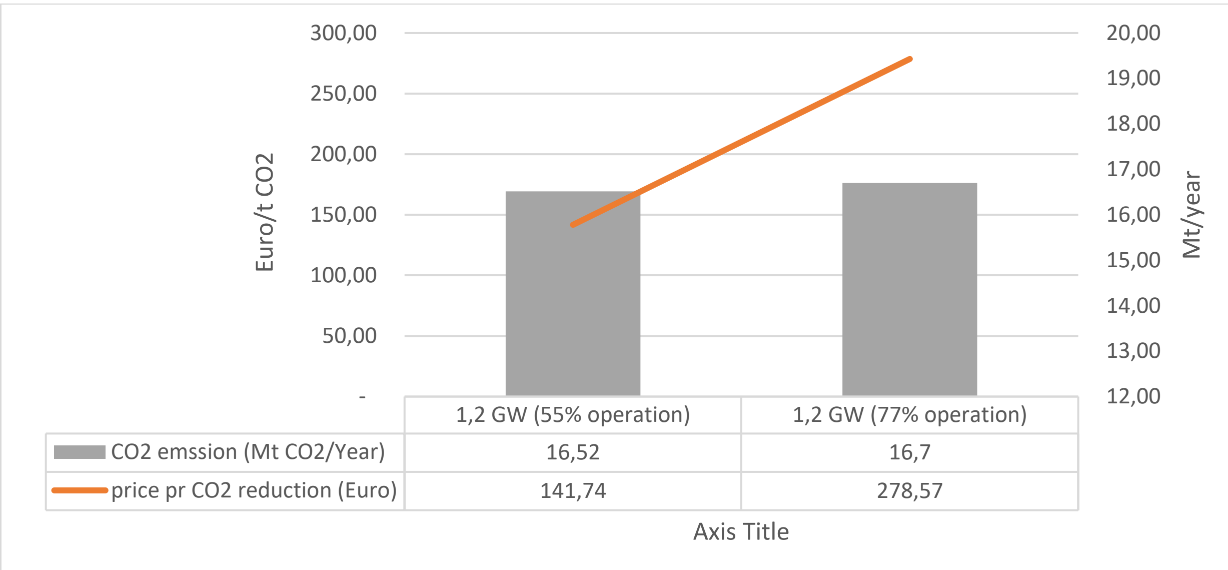


Figure 14 – the difference between when PtX is operated flexible and non flexible

9.3.2. Overview of framework

To give a fast overview, the table below sums up the main characteristics of framework for the model simulation, based on the previous. All the scenarios are based on this.

The design of the energy system analysis	
Flexible operation	An average operation of 50-60% of the capacity
CEEP	Fixed (3,2 TWh/year)
Fuel demand	22,5 TWh, divided into the different modes of transport
RES	Fixed solar PVs and onshore wind (4,8 GW of onshore wind and 5 GW of PV) Offshore wind to cover the electricity demand
Cost of infrastructure	Fixed infrastructure prices
Storage	The storage will increase along with an increase in PtX capacity

Figure 15 - an overview of the main characteristics of the model simulation.

9.4 The four scenarios

Four different scenarios with different amounts of PtX in Denmark in 2030. One scenario without any PtX production. Two scenarios consisting of 4 and 6 GW of PtX, reflect the government's PtX strategy. And lastly, a scenario of 1,2 GW, to simulate the amount of PtX which, by IDA2030, is assessed to be needed to reach the Danish goal of a 70% reduction while being technically and economically feasible. The scenarios have been analysed in EnergyPLAN with the previously presented inputs to run the scenarios according to a smart energy system regulation and to match the fuel demand.

The table below shows the input of the different scenarios, with the capacity, the fuel possible to produce from the capacity, how large a share of the total demand of fuel it covers, and the offshore wind needed for the system to run flexible and with the fixed CEEP, corresponding to the framework.

Electrofuels	0 GW	1,2 GW	4 GW	6 GW
E-jet fuel (TWh)	0	0,01	3,165	7,27
DME/Methanol (TWh)	0	2,82	4,1	4,97
Ammonia (TWh)	0	0,16	1,38	2,25
Pct. PtX demand	0%	13%	38%	64%
Offshore wind (GW)	5,2	6,6	9,5	11,9
Onshore wind (GW)	4,8			
Photovoltaic (GW)	5,0			

Figure 16 - Input in the scenarios

Without any PtX capacity, the system needs 5,2 GW of offshore wind, supplemented by 4,8 GW of onshore wind and 5 GW of PVs to run the system as defined in *Figure 15*. When increasing the capacity of electrolysis, the demand for RE increases, as previously mentioned only the offshore wind capacity is increased between the scenarios to ensure comparability. In a system with 1,2 GW of electrolyser 13% of the fuel demand for transport can be covered by e-fuels, this requires an addition of 1,4 GW of offshore wind.

Following the goal of increasing the PtX capacity to 4-6 GW. The production of e-fuels will be able to cover 38-64% of the fuel demand from transport. Which for instance could cover 20% heavy road transport, 24-55% aviation, and 42-69% shipping.

Today there is no production of hydrogen-based methanol or e-fuels in Denmark, except for a test plant by Aalborg University (Hydrogen Denmark 2020). Based on "Denmark's Climate Status and Outlook 2022", KF22, which is a forecast based on a frozen policy with exciting measures considered, Denmark will have an electrolyser capacity of only 254 MW in 2030. It is however also stated that there are already projects announced with a total capacity of 7 GW, however, only the projects with a settled investment plan are included in the forecast. (Energistyrelsen 2022b)

With 6 GW of PtX, operated flexible, the Danish energy system will require RE corresponding to an offshore wind capacity of 11,9 GW supplemented by the 4,8 GW of onshore wind and 5 GW of PVs.

Today there are 2,3 GW of offshore wind, 4,7 GW of onshore and 2 GW of PVs. based on KF22, the capacity of offshore wind is forecasted to be increased to 6,9 GW in 2030.(Energistyrelsen 2022a) Based on this forecast there would be enough wind to supply the scenario with a production of 1,12 GW of PtX. To supply 4-6 GW of PtX, the offshore wind capacity should be increased by 2,6-5 GW or onshore/PV capacity equivalent to the energy production of that amount of offshore wind.

9.5 Results

Scenarios		**0 GW**	**1,2 GW**	**4 GW**	**6 GW**
Electrolysis capacity	*GW*	0 GW	1,12	4	6
CO2 emission	*Mt*	17,5	16,5	14,7	13,3
Total annual cost	*Mio Euro*	22.904	23.049	23.423	23.860
CEEP	*TWh/year*	3,2			
Fuel ex RES	*TWh/year*	113,3	109,0	101,4	97,3
Fuel incl RES	*TWh/year*	162,4	164,7	169,9	176,5
Biomass	*TWh/year*	44,6	44,4	44,0	44,6
Oil consumption	*TWh/year*	49,8	46,8	41,2	35,3
Offshore wind	*GW*	5,2	6,6	9,5	11,9
RES share	*%*	57,7	60,8	66,2	70,3
Price pr CO2 reduction, compared to 0 GW scenario	*Euro/ton*	-	141,7	182,1	226,5

Figure 17 - Results of the scenarios

The results are presented with a focus on the environmental and economic impact on the system. Denmark has an aim of reducing its carbon footprint and reaching carbon neutrality by 2050. The reduction of CO2 emissions is therefore used as a measure for the environmental impact of changes in the system. Further, the consumption of biomass is an important factor, as the amount of biomass used should be kept at a sustainable level. The economic impact is measured by increase in the system cost.

The total annual cost of the Danish 2030 energy system without any PtX capacity is 22.904 Mio EUR, while the emission of CO2 is 17,5 TWh/year. To reach the 70% reduction goal, the system needs 1,2 GW of electrolyser, according to IDA2030. Reaching the 70% reduction goal is seen as a premise, therefore the implementation of 4-6 GW electrolysers is primarily compared to this, while the scenario without electrolysis is used to understand how the introduction of PtX influence the system.

For all scenarios, it is seen that when the capacity of PtX is increased, the total annual cost increases while the CO2 emission decreases. The increase in PtX capacity is reducing the CO2 emission from 16,5 Mt in the scenario with 1,2 GW PtX to 13,3 Mt in the 6 GW scenario, a reduction of 19% in the overall carbon emission from the energy-consuming sectors. While the price increases by 956 Mio EUR when building 6 GW of electrolysis. This is equal to an increase in system cost of 4%.

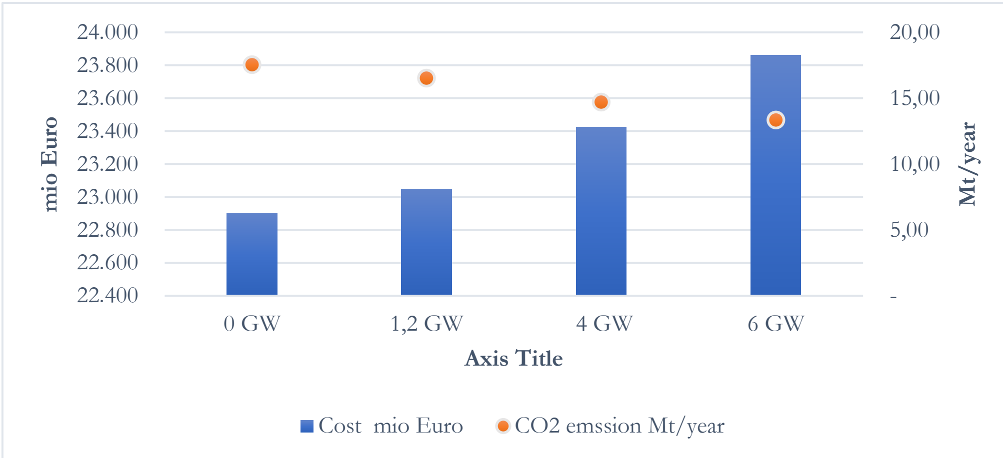


Figure 18 The price and emission of CO2 in the different scenarios

The price pr CO2 reduction is also increasing, meaning that the first GW of electrolysis is more cost-efficient for the system. From zero to 1,2 GW the cost pr CO2 reduction is 142 Mio Euro. Whereas the increase in cost for the 6 GW scenario is 226 Mio EUR/CO2 reduction. This indicates that the e-fuels cannot compete with prices of the fossil fuels when looking at the cost of the system.

In IDA2030 the price of CO2 reduction is also calculated, the results show that in some sectors decreasing the CO2 emission even reduce the cost of the system. (Lund et al. 2020) The prices found in IDA2030 is plotted with the prices pr CO2 reduction based on PtX in *Figure 19*.

There is a limit of how much each sector can reduce its emissions therefore it would not be sufficient to only reduce the emissions from electricity production. There is a need for reductions in all sectors. However, to get most reduction for the money, reductions in other sectors should be prioritised.

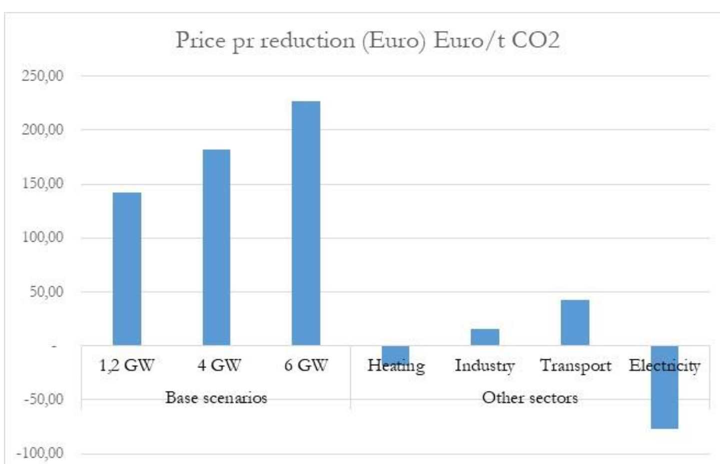


Figure 19 a comperison of the prices for CO2 reduction by PtX with other sectors. The data from the other sectors is from: (Lund et al. 2020)

In the four scenarios, the biomass consumption is stable with a decrease in biomass use for the combined heat and power plants and an increase in the use of biomass in the boilers and power plants. To avoid CEEP the system uses boilers to replace CHP in hours without the need for electricity. Further, the system balances the production both based on electricity and heat demand, meaning that in hours with a need for power but no heat the electricity production will be based on power plants. More flexibility in the system, for instance in the heating sector, with larger heat storage or an increase in the heat pump capacity, could decrease the biomass consumption and utilize the RE.

As mentioned in the introduction, the transition away from fossil fuels will challenge the flexibility of the system, as fossil fuels are a great source of flexibility. It was further stated that when the system in the future will be based on fluctuating sources of energy, like wind and solar power, PtX is a great technology providing flexibility. The energy system analysis confirms this statement, looking at the amount of RES the system can integrate. With the introduction of 6 GW of PtX, the RES share is increased from covering 58% to 70% of the total energy supply, decreasing the fuel ex. RES.

9.6 Sensitivity analysis

As the future is uncertain, any methodology, trying to forecast it is associated with assumptions. These assumptions can be debated. The sensitivity analysis will test some of these assumptions and how it will change the results if the future varies from the assumptions. The following three different sensitivities are run through EnergyPLAN:

- How will the system react if there is not enough RE (excl. biomass) capacity to cover the electricity demand?
- How will the system cost be affected if the oil prices are increased?
- How will the system cost change if the prices of wind turbines are increased?

9.6.1. How will the system react if there is not enough RE (excl. biomass) capacity to cover the electricity demand?

One of the most debatable assumptions is whether there will be built enough RE-capacity to cover the energy demand from 4-6 GW of PtX(Capion and Sørensen 2022; Klimarådet 2022; Brintbranchen 2022). It is therefore tested how the system will react if the RE capacity is kept fixed while the PtX capacity is increased. The RE is fixed at the same amount as in the scenario without PtX (5,2 GW of offshore wind, supplemented by 4,8 GW of onshore wind and 5 GW of PVs). To produce the electricity needed to supply the PtX, the electricity is produced at power plants. This leads to an increase in the use of fossil fuels and biomass which increase the CO_2 emissions. Integrating 6 GW of electrolyser will entail an emission of 18 Mt of CO_2, being 0,5 Mt more than in the scenario without PtX despite the reduction of oil used for transport. Besides the increase in emissions, the cost of the system also increases compared to the system with offshore wind to cover the energy demand. Comparing the 1,2 GW scenarios, the price difference is 30 Mio Euro. The difference is significant higher when comparing the 6GW scenarios, here the price difference is around 1.700 Mio Euros. *Chart 21* illustrates all the scenarios based on emissions and system costs.

Based on this the importance of building out RE to cover the PtX potential can be emphasised. This scenario is however not expected to be a reflection of a real scenario, as the capacity of RE in this test is significantly lower than the forecasted amount of RE (Energistyrelsen 2022a)

9.6.2. How will the system cost be affected if the oil prices are increased?

As concluded in the analysis the prices of e-fuels cannot compete with the prices of fossil fuels in the model. In the scenarios the prices are based on IDA2030, thus the current prices of fossil fuels are significantly higher than the ones used in the model. The oil prices used for the sensitivity are based on the current Danish weekly oil prices from the European Commission. *Tabel 20* gives an overview of the prices from IDA2030, compared with the current fuel prices used in this sensitivity analysis.

	Base scenarios	Sensitivity
Fuel oil (Euro/GJ)	10,4	26,44
Diesel gasoil (Euro/GJ)	15	34,4
Petrol/JP (Euro/GJ)	14,9	34,5

Tabel 20 Prices of the oil prices in the scenarios

When using the current oil prices, the system cost increases compared to the system cost of the basic scenarios. Comparing the scenarios without any PtX the cost increases by more than 3.000 Mio Euro, solely from increasing the oil prices. However, when more electrolyser capacity is implemented in the system with the current oil prices, the total annual cost is almost stable. Indicating that the cost of producing e-fuels is similar to the current high prices of oil. The same CO2 reduction will be achieved meaning that the implementation of electrolysers in a system with a high cost of oil, would be beneficial.

9.6.3. How will the system cost change if the prices of wind turbines are increased?

Lastly, it is tested what an increase in the investment cost of wind turbines will entail. This could be caused by increasing steel prices, or other conditions influencing the prices of wind turbines.

The result of this test shows that increasing prices of wind turbines will entail an addition to the cost of the system in all scenarios. The price increase is smallest in the scenario without PtX and increases with the implementation of more PtX as the capacity of wind energy increases. This sensitivity could likewise be conducted with changes in the cost of electrolysers, the infrastructure, or other technologies in the supply chain for e-fuels.

Chart 21 below shows how the different sensibility analyses influence the system based on price and CO2 emissions.

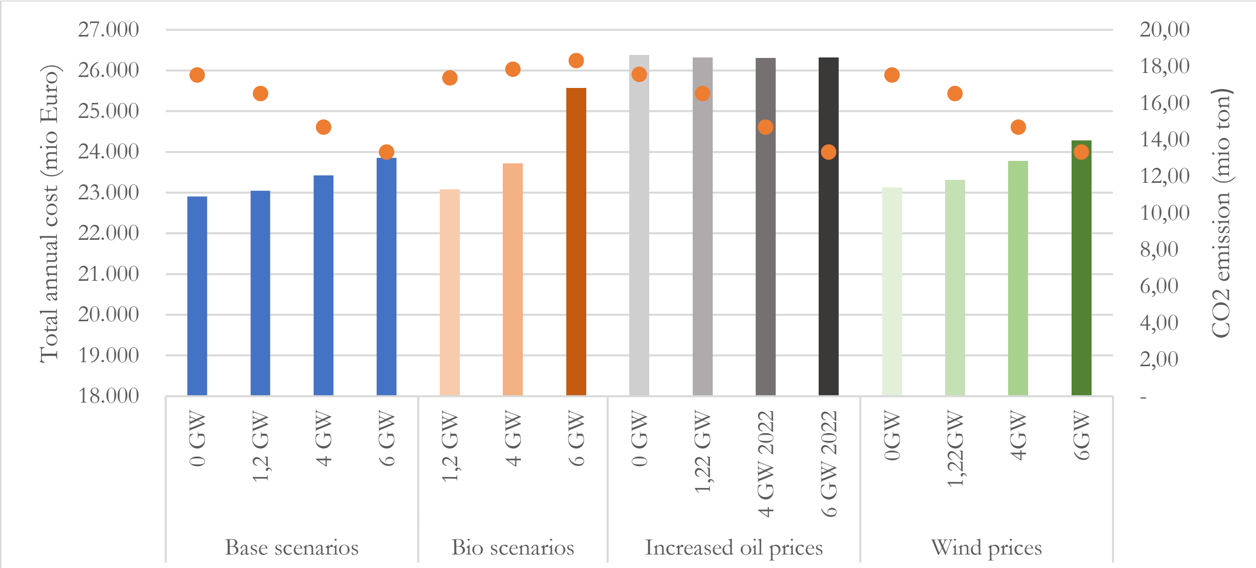


Chart 21 - The different sensitivities compared to the base scenarios on total annual cost and CO2 emissions

9.7 The impact of 4-6 GW of PtX on the energy system

Implementing 4-6 GW of PtX can reduce the CO2 emission from the energy system by up to 24%, this is a significant reduction. However, it requires a lot of energy, which must be supplied by RE (excl. biomass). The analysis shows that there is a need for 9,5-11,9 GW of offshore wind to cover the demand for electricity if the government's strategy of 4-6 GW of PtX is implemented. If there is not enough RE capacity, the implementation will be more expensive and the implementation of PtX can end up resulting in an increase in the carbon emission despite the reduction in oil consumption for transport.

The cost of e-fuels is not competitive with fossil fuels in the basic scenarios, however, in the sensitivity analysis the system was run with the current oil prices (May 2022). With the current oil prices, e-fuels are competitive with fossil fuels, assessed from a system cost perspective. The competitiveness of e-fuels is therefore reliant on how future oil prices will develop. If the prices fall, then there is a need for market regulation to make e-fuels competitive with fossil fuels. The value of carbon reductions should be assessed from a socio-economic perspective.

Compared to the cost of achieving carbon reduction in other sectors, PtX is an expensive solution, however, to reach carbon neutrality reductions need to be achieved in all sectors. As e-fuels are needed to reach carbon neutrality in the transport sector, the implementation is therefore necessary towards 2050. For the most cost-efficient reductions toward 2030, the cost should however be considered.

10. Analysing roadmaps to implementing PtX

In the previous analysis, it was investigated how the integration of 4-6 GW PtX will affect the energy system in 2030. It was found that the system cost will increase, but the carbon emissions can be reduced significantly. Despite the cost, PtX is needed to decarbonize the Danish transport. The question is what initiatives are needed to successfully implement PtX in the Danish energy system. Several actors have contributed with suggestion to this throughout the last couple of years. This analysis will map and analyse those suggestions based on five roadmap/strategies/suggestions for implementation of PtX, from here on referred to as roadmaps.

The following will first present the main points agreed on in the political agreement to develop and promote PtX. (Folketinget 2022) To compare the initiative agreed on in the agreement to the initiatives from five roadmaps.

10.1 The political agreement to develop and promote PtX

The following will go through the main elements of the political agreement to develop and promote PtX.

First of all, the agreement has set the goal of 4-6 GW of electrolyser in 2030, which is the point of departure for this thesis, as it has been perceived as a very ambitious goal. The goal is not solely to have 4-6 GW of PtX, it also needs to be based on RE. As found in the energy system analysis, this requires a significant outbuild of RE. The aim is that even with a capacity of 4-6 GW, Denmark should still be a net exporter of green energy in 2030. To support this deployment, it is stated in the agreement that the government will publish a plan for the deployment of RE during 2022. As the biggest need for PtX is in the transport sector. The government will further come up with proposals for the green transition of aviation in 2022, and heavy-duty transport and shipping in 2022 or 2023. It is emphasized that there is a need for regulation from European scale, introducing common European standards, for a well-functioning PtX market.

Looking at support for developing PtX, it is stated that PtX needs to be deployed as much as possible on market terms. In the climate agreement for energy and industry 2020, there was set a funding pool aside for industrialisation and upscaling of PtX. The funding pool consists of 1,25 billion DKK set aside for a tender for production of green hydrogen. The tender will be distributed to the bidders with the lowest production cost and will be paid per produced amount of green hydrogen. Further European funding pools and innovation funds are mentioned as possibilities for economic support.

The costs of electricity, especially the tariffs are also a focus in the plan. To reduce the cost of tariffs, the plan has three solutions: Direct lines, geographically differentiated tariffs, and local collective tariffs. Electrolysis will increase the load of the grid, however, if the PtX is placed strategically close to production and in places where there is excess capacity on the grid, the demand for expansion of the grid will be minimized, and this will be rewarded with a reduced tariff.

It is further agreed that there is a need for a hydrogen infrastructure to distribute and store the hydrogen produced in electrolysers. The grid should both facilitate the national distribution, but also the export of hydrogen. Planning of export through pipelines needs to be made in cooperation with the neighbouring countries (especially important is Germany).

Lastly, a PtX task force should be formed to underpin the Danish hydrogen market and infrastructure. The task force shall coordinate across the state authorities and assure continuous communication with the relevant actors. The task force needs to identify and manage regulation and law barriers for PtX products and strengthen the framework conditions for the production, transport, and usage of hydrogen and PtX products. Further, the task force needs to create tools to enhance the socio-economic relating to the placement of PtX and potential usage of excess heat.

10.2 Roadmaps to PtX

The politic agreement is compared with five roadmaps to analyse what measurements are necessary from the key actors' and knowledge institutions' perspective, and whether this is integrated in the political agreement. The following roadmaps has been analysed:

Danish roadmap for large-scale implementation of electrolysers: In 2017 Aalborg University published a roadmap to large scale implementations of electrolysers. Looking into the development needed before 2020, between 2020-2025, between 2030-2035 and after 2035.

Recommendations for a Danish Power-to-X strategy: In November 2020 Green Power Denmark published their *Recommendations for a Danish Power-to-X strategy*. Green Power Denmark is a business organization representing members from across the energy sector.

Recommendations for a strategy for PtX and CCU (translated from the Danish title: Anbefalinger til strategi for PtX og CCU) : The Confederation of Danish Industry (DI) published in June 2021 the report *Recommendations for a strategy for PtX and CCU*. The recommendations were made by a so-called advisory board for PtX/CCU and CCS consisting of more than 30 companies. DI is a business and employers' organisation representing approximately 19,000 companies in Denmark.

VE 2.0 – Hydrogen and PtX strategy (translated from the Danish title: VE 2.0 – brint- og PtX-strategi: Hydrogen Denmark is an interest organization consisting of several Danish hydrogen and PtX stakeholders, seeking to promote upscaling and implementation of hydrogen-based solutions. Hydrogen Denmark published in 2020 an analysis of the potentials for large scale hydrogen and PtX in Denmark, under the title *VE 2.0 – Hydrogen and PtX strategy*

Roadmap for Green Fuels in Transport and Industry: The fifth roadmap analysed is called *Roadmap for Green Fuels in Transport and Industry* and is made in cooperation between Danish universities, knowledge institutions and cluster organizations (e.g., DTU, Energy Cluster Denmark, GTS, etc.). The roadmap is made for Innovation Fund Denmark (IFD)'s call for a roadmap for *Green fuels for transport and industry (Power-to-X, etc.).*

10.3 The five roadmaps:

To get a fast overview of the five roadmaps, Table 22 and Table 23 present the suggestions from the roadmaps divided into 5 topics. The following will dive into those topics and the different ideas of needed measures between the roadmaps/strategies.

10.3.1. Capacity goals

Several of the roadmap emphasise that setting a goal for the deployment of PtX is essential, as a capacity goal gives a planning prospect and a direction that both public and private actors can navigate after. Further, it will show investors the Danish ambitions. Setting the goal of 4-6 GW in the political agreement is therefore considered an important step.

Compared with previous roadmaps, the government goal of 4-6 GW is in the high end. Reaching 6 GW corresponds to the ambitions from Hydrogen Denmark which suggests 1 GW in 2025 and 6 GW in 2030. DI and IFD does not specify what the goal should be but emphasizes the need for a goal to express Denmark's ambitions. Green power Denmark proposes a goal of at least 3 GW.

Since the roadmap from AAU was published, there has been a fast development of the PtX. The expectation in the AAU roadmap is therefore significantly lower with an expectation of 1 GW in 2035.

Looking into the capacity goals it is important to notice that Hydrogen Denmark is an interest organisation, seeking to promote upscaling and implementation of hydrogen-based solutions (Hydrogen Denmark n.d.). DI and Green Power Denmark are also interest organisations representing the industry, promoting the interest of some of the market actors. Ensuring a good business economy is therefore also major interest of them.

Besides the roadmaps Klimarådet (2022) and Concito (2022) has commented on the goal, supporting the ambition but also expressing a concern for whether the deployment of RE can follow the pace (Klimarådet 2022; Capion and Sørensen 2022). Klimarådet suggest that 4-6 GW is used as an aim, but with the reservation that the deployment of RE has to follow the demand for electricity(Klimarådet 2022). As shown in the sensitivity analysis it is important that the electricity supply from PtX is covered by RE. To avoid an increase in both cost and CO2 emissions. In the political agreement emphasis is also being put on the need for the PtX to be supplied by RE, as the aim is to be a net exporter of green energy. According to IFD a consequence of the implementation of PtX is that Denmark will become a net importer of electricity and that it removes the possibility to export electricity to Europe. To ensure the supply of RE, emphasis is put on the need for a plan for deploying the RE capacity among all the actors.(Dansk Energi 2020; Dansk Industri 2020; Skov and Mathiesen 2017; Hydrogen Denmark 2020; DTU et al. 2021)

10.3.2. Market regulation

One of the obstacles for the implementation of PtX is that it is in competition with fossil fuels. The energy system analysis found that assessed on system cost, e-fuels can compete with the current high oil prices. However, according to Green power Denmark e-fuels are still far from cost-competitive with fossil fuels. It should be noted that the oil prices were lower when this was published and is therefore not appliable for the current oil prices. Independent on the oil prices PtX is a costly was to reduce the carbon emissions. To make the technology more cost-effective there is a need for further development and upscaling (Skov and Mathiesen 2017; Hydrogen Denmark 2020), however without consumers willing to pay higher prices, there is no demand pulling actors to invest in scaling up the technology. This can be addressed as the egg-and-chicken problem, as the developers are depending on a demand and the consumers are dependent on a further development to decrease prices. Green power Denmark referred to this as the PtX paradox. (Dansk Energi 2020)

As elaborated upon in *8.2 Methodology*: the market should be constructed to support the desired development, assessed as the best option from a socioeconomic perspective, by making the desired development attractive from a business economy perspective. (Hvelplund and Lund 1998)
In accordance with this AAU's roadmap emphasizes that the market conditions need to support the desired development, creating good conditions for green technologies. For instance, it should be constructed to supports flexibility and the integration of RE. It is suggested that the market design should be developed based on learnings from demonstration plants testing different market conditions. (Skov and Mathiesen 2017)

As mentioned in *6.3 From planning in silos to a smart energy system* the current market is not designed to facilitate a future with large penetration of fluctuating energy, as fuels today provides the balanced to the system. As the energy production increasingly will become based on fluctuating sources, this flexibility needs to be facilitated by other parts of the system. To initiate this, it should be awarded balancing the system, to create incentives for a flexible operation. This importance of this is supported by the energy system analysis showing how flexible operation of PtX is beneficial both from a system cost and environmental perspective.

The current design of tariffs is a condition which the roadmaps all mention to be an obstacle for PtX. The political agreement also focus on this and has agreed on three solutions. 1) A tariff reduction when PtX production is in direct line with RE. 2) Geographically differentiated tariffs to make it attractive to locate the PtX close to producers and places with extra capacity in the grid, to prevent unnecessary expansion of the grid. 3) a beneficial tariff for local energy collectives.

Another way to support the desired development away from the use of fossil fuels is using CO2-taxation, this is an initiative mentioned by Hydrogen Denmark, DI, and IFD. (Hydrogen Denmark 2020; Dansk Industri 2020; DTU et al. 2021)

10.3.3. Government subsidy schemes and support

To reach 4-6 GW of PtX in 2030, the necessary investments need to be made within few years. When investing in new technologies, or technologies new to the market, the risk associated with the investment is big. This makes the investment less attractive to investors. To minimize the risk of investment the state can provide support to projects with different economic means to reduce this risk (Wüstenhagen and Menichetti 2012). DI suggest risk minimising though fixed prices designed as contract for difference, CfD. The CfD-model removes a part of the risk as the producer of electrofuel or hydrogen will receive the same price pr produced unit independent of the market price. (Dansk Industri 2020)

The political agreement has set 1,25 billion Danish kr. aside for a tender. The tender is designed to be granted as a price premium, an additional income per produced amount of hydrogen for the winning bidders. The argument for aiming the subsidy to hydrogen production, is that this is the first step in the PtX production chain, meaning that all PtX actors (meeting the additional requirements) can bid for this tender.

1,25 billions kr is below the estimated of needed support by the three interest organizations. Hydrogen Denmark, DI and Green Power Denmark state that there is need for more support to match the subsidy level in other countries, especially Germany. AAU and IFD focus on the need for support for demonstration and pilot projects to ensure development and innovation. (Skov and Mathiesen 2017; DTU et al. 2021)

(Dansk Energi 2020; Dansk Industri 2020; Skov and Mathiesen 2017; Hydrogen Denmark 2020; DTU et al. 2021)

10.3.4. Infrastructure

Infrastructure is a great focus in all the roadmaps. DI, Hydrogen Denmark and AAU express that PtX should be located close to existing infrastructure and energy producers, to limit the need for building new infrastructure. For instance, close by the planned energy islands. AAU suggest the involvement of municipalities in the process of locating future plants. IFD suggest further using stakeholder and citizen involvement for social acceptance of the projects.

IFD even argues that the hydrogen grid and storge will be the driver for market implementation. This is confirmed by DI and Hydrogen Denmark stating that export of hydrogen to neighbouring countries is a key to scaling up hydrogen production. Its further stated that pipeline is most cost-efficient. The political agreement likewise finds the infrastructure and storage essential to distribute and store the hydrogen produced in electrolysers. Stating that the grid should both facilitate the national distribution, but also the export of hydrogen.

Besides the hydrogen infrastructure, fuelling infrastructures for heavy duty- and maritime transport need to be implemented. The electricity grid also needs an expansion as a results of the increase in energy demand and production, as mentioned in *10.3.2 Market regulation* this should however be minimized through market regulation.

(Dansk Energi 2020; Dansk Industri 2020; Skov and Mathiesen 2017; Hydrogen Denmark 2020; DTU et al. 2021)

10.3.5. Research and development of technologies

As mentioned in *6.2 Power to X as an alternative to fossil fuels and the role of biofuels,* the technologies has a rather high TRL, thus Hydrogen Denmark emphasize that the technologies can play a role in large scale. Even with a high TRL, the actors agree that there should be ongoing research and development especially focusing on the more complex e-fuels and to decrease the cost of the technology. This requires testing and demonstration of the technologies and regulation. As the technologies are at different stages, different activities are needed to increase the readiness level. (IFD)

To ensure continuously involvement and knowledge sharing with PtX stakeholders, the political agreement has decided on creating a PtX taskforce. This was one of the suggestions by Green power Denmark. The roadmap by AAU, suggests establishment of a knowledge centre as an alternative.

A premise for a sustainable operation of PtX is that it utilizes RE. In order to do so, the PtX needs to be operated flexible. One thing is doing it in EnergyPLAN but to ensure flexible operation in real life, the market needs to be designed to support such operation. The roadmap by IFD state that there is a need for research on how to ensure a flexible operation of PtX.

Dansk Energi 2020; Skov and Mathiesen 2017; Hydrogen Denmark 2020; DTU et al. 2021)

10.3.6. Road transport

Heavy road transport is assessed to be one of the demands PtX need to cover parts of. In the energy system analysis 20% of the heavy road transport demand was covered by e-fuels. There are many different perceptions of what propellant heavy road transport will be using in the future, from fully electric driven, to driving on hydrogen or e-fuel.

To make hydrogen and e-fuels cost competitive with fossil fuels, the roadmaps suggest implementing blend standards or tax reductions on 0-emission cars. This should preferably be regulated from European scale, to ensure fair competition across Europe. Further as touch upon in *10.3.4 Infrastructure*, a fuelling infrastructure is needed if hydrogen shall be used as fuel for road transport.

IFD suggest that methanol/DME should be used in light duty road transport for a period, as the transition to electric vehicles is happening too slowly. According to IFD, this will have the additional effect of securing a stable demand for e-fuels, de-risking the investment. The other roadmaps focus solely on heavy road transport as an off taker.

The political agreement state that a plan for the green transition of heavy road transport will be published in 2022 or 2023.

(Dansk Energi 2020; Dansk Industri 2020; Skov and Mathiesen 2017; Hydrogen Denmark 2020; DTU et al. 2021)

10.3.7. Maritime transport and aviation

As identified in *9.1 The demand for PtX in 2030*, aviation and maritime transport account for the biggest demand for PtX. Thus, 31% of the emissions from transport is assessed to be emitted from aviation and maritime transport (Kany et al. 2022), most of the transport in these sectors are considered international transport and therefore not reported as national totals or considered when Denmark strikes to achieve the climate goal of a 70% CO2 reduction. DI argues that one way to promote the demand for PtX is by including the sectors as a part of the climate goal.

The political agreement state that the government will publish a proposal for the green transition of aviation in 2022 and for maritime transport during 2022 or 2023.

Technically the TRL is high for maritime transport and is therefore expected to be able to use e-fuels as propellant within a short timeframe, however according to IFD it is not cheap enough to compete with shipping using fossil fuels. To make e-fuels attractive for shipping there is need for international regulation, as it is an international market. (Hydrogen Denmark 2020; Dansk Industri 2020; Dansk Energi 2020)

For aviation the picture is different. The TRL is 5-6 meaning that it is not developed to be implemented on large scale but requires further research. Despite this, hydrogen Denmark set the ambition for aiming at covering 30% of the aviation fuel with e-fuel. AAU also suggests upscaling jet fuel production.(Hydrogen Denmark 2020; Skov and Mathiesen 2017) To increase the demand, DI suggest a tavel tax for aviation based on the climate effect. When e-kerosene is developed and regulated, e-kerosene will have the same composition as fossil kerosene, making it fast to drop-in, as there is no need for changes on the demand side (Dansk Energi 2020)

(Dansk Energi 2020; Dansk Industri 2020; Skov and Mathiesen 2017; Hydrogen Denmark 2020; DTU et al. 2021)

10.3.8. Other

In addition to the above-mentioned, the roadmaps mentioned some initiatives that did not fit into the categories. These will be mentioned in the following.

One of the inicitative in the roadmap by DI is a strategic planning of the CO2 resources. The CO2 should to be used where it adds most value. The weighing of whether CO2 from carbon capture from point sources should be stored or utilized in PtX needs to be planned considering CO2 a limited resource in high demand. The CO2 must be from a biogenic source for the end-fuel to be considered green. The total resource is estimated to be 12-13 Mio ton CO2/year in 2030, however decreasing to 6 Mio ton/year in 2050. (Dansk Energi 2021) Based on the energy system analysis it was found that with a capacity of 6 GW and a fuel output primarily consisting of cabon based fuel, there is a yearly demand of 3,5 Mt CO_2. This depends on end-fuel demand, as a higher share of ammonia or hydrogen without operation will reduce the carbon demand.

Another initiative is to ensure workforce, IFD suggest that the process of educating workforce must be initiated.

Lastly, lobbying for European or international regulation is brought up by most of the actors. The focus is to ensure the demand in the transport sector.

(Dansk Energi 2020; Dansk Industri 2020; Skov and Mathiesen 2017; Hydrogen Denmark 2020; DTU et al. 2021)

	Hydrogen Denmark (2020)	The Confederation of Danish Industry (2021)	Green power Denmark (2020)
Capacity goal	• 1 GW in 2025 • 6 GW in 2030	• Not specified, but there needs to be a goal suiting the ambitions and considering the exciting plans with a capacity of 6,7 GW in 2030	• 3+ GW in 2030 → leading to 2,5 m ton CO2 reduction
Regulation	• Taxes on fossil fuels and better conditions to produce hydrogen. • Focus on tariffs	• Optimize the capacity with dynamic tariffs. Other tariffs if the RE is directly linked to the electrolyser, etc. • Need to plan across the sectors, as it is a cross-sectoral technology. • Risk minimizing with fixed prices, CfD • CO2 taxes	• Develop tariff and grid connection models so that payment for the grid is consistent with load and load alleviation
Government support	• An investment of at least 5 billion DKK, as PtX cannot yet compete with fossil fuels.	• More government support, when other countries (e.g., Germany) have greater financial support, it makes it hard for companies to compete on the Danish market.	• 10 billion DKK between 2021 and 2030 to kick-start and industrialise PtX • 0,5 GW value chain projects (2-5 projects). Tenders to ensure the capacity reaches 3+ GW • Create tender for value chain projects
Road transport	• Create incentives to drive in 0-emission vehicles, by tax reductions	• Suggests the use of e-fuels and biofuels in combustion engines until 2030	• Introduce requirements that support CO2 displacement and ensure greater use of PtX for road transport • CAPEX subsidies for the purchase of hydrogen trucks before 2030 • Support hydrogen transport in the short-term with a regulatory framework
Infrastructure	• Electrolysers need to be placed strategically with access to the electricity transmission grid and district heating grid. Further, there is a need to build a grid which connects Denmark to the rest of Europe • Fueling infrastructure for heavy duty transport	• The possibility to export hydrogen is a key to large scale implementation of PtX-production in DK. Transport through pipelines is the most cost-effective. • Transmission infrastructure, to use the electricity from energy islands.	• Develop and establish a Danish hydrogen grid with connections to neighbouring countries and assess the need for hydrogen storage in the long term • Plan for the expansion of hydrogen filling stations for heavy transport • Work towards PtX-ready port infrastructure in the EU
R&D	• To decrease the cost of the technology, there is still a need for further research and development.		• Establish a PtX taskforce. • Strong governance, where the business sector is continuously involved and consulted regarding future adjustments to the PtX strategy
Aviation and shipping	• 30% e-fuels for aviation in 2030. • All ferries should be CO2 neutral by 2030. • Denmark should support a carbon neural international shipping with a focus on ammoniac	• Reducing the CO2 emission in aviation and shipping should be a part of the Danish climate goal • Climate fond/tax based on the climate effect from travel to create a demand for e-fuels.	• Establish a climate fund based on climate contributions from passengers • Introduce blending requirements of PtX-based aviation fuels • Work towards joint EU action for international approval of all relevant types of PtX-based aviation fuels • Ensure national ferry services are green and establish a Scandinavian partnership for fossil-free ferry service between the countries
Other	• Need for common European standards for green hydrogen	• Needs to assure CO2 to PtX – planning between CCS and PtX. PtX should be prioritized. • Partnerships are important both nationally and internationally • Pressure the EU on certification of renewable hydrogen, green CO2 and renewable hydrogen-based fuels	• Lobby for European regulation • Take advantage of EU funds and opportunities in IPCEI

Table 22 - Overview of the roadmaps (Dansk Industri 2020; Dansk Energi 2020; Hydrogen Denmark 2020)

	Aalborg University (2017)	Innovation fund Denmark (2021)
Capacity goal	• No capacity goal, but an expectation of 1000 MW in 2035	• No suggestion for capacity goal, but emphasize the need for strategy from the Danish state for the actors
Regulation	• Create a market model that supports flexible operation to ensure maximization of integration of RE, and support PtX as a part of the smart energy system. • The market needs to be stable to encourage investments. • Ensure the market conditions support the desired development, creating good conditions for green technologies. New technologies should not compete with fossil fuels in the established system. • The future market design and conditions should be based on the experiences in the demonstration plants	• The market needs to be regulated such that CO2 reductions are rewarded. For e-fuels to compete with fossil fuels the government need to ensure financial incentives, either using requirements, taxes or subsidies. (the industry favour CO2 tax) • Redesign of the tariffs
Government support	• Support pilot and demonstration projects (e.g., 30% investments subsidy)	• Propose a public co-financing of projects and financing of innovation, research and development. Some financing can be obtained through innovation funds or EU funding support schemes. • The government should ensure de-risking of investments (co-financing, ensuring a demand through legislation or offtake for public transport.
Road transport	• New Blend standards with electrofuels acknowledged in legislation. Should be implemented on a European level. • Fleet testing to generate knowledge on vehicle performance.	• The transition to electric cars is too slow, therefore, methanol and DME should be promoted as intermediate fuels. This will further ensure a stable-off take of methanol de-risking the investments in PtX.
Infrastructure	• Electrolyser should be planned to be in locations with the best connection to the needed infrastructure. The locations should be identified on the municipal level • Fuelling infrastructure for heavy road transport need to be implemented • The need for infrastructure, including storage needs to be investigated and tested.	• Hydrogen grid will drive the market implementation • To upscale the green hydrogen production it is crucial to plan for a hydrogen grid and storage, this should be done in a thorough analysis including stakeholders. This is also expected to attract international investments. • Large scale demonstration of storage
R&D	• Establish a knowledge centre for knowledge sharing between the producers of electrolyser technology and researchers. • Testing and demonstration of the technologies and regulations. Upscale from successful demonstration, to assess potential issues in full implementation. As the technologies are at different stages, different activities are needed to increase the readiness level.	• Establish end-to-end demonstration projects, with a focus on the entire chain from production to consumption. Partner up with private companies with an interest in developing or using e-fuels. • Study and learn from previous cases successfully implementing new fuels. • Research on how to operate the PtX flexible to deliver system service to the electricity grid and to quickly react to price signals • Develop new digital infrastructure and market solutions to support the future PtX market
Aviation and shipping	• Upscale jet fuel production • Fleet testing of different fuels/electricity as a propellant	• Ammonia engines should be developed and approved as a fuel for maritime transport • Research and development of methanol to jet fuel processes and a demonstration plant (or approve gasoline as jet fuel) • Shipping has a high readiness level, but the cost of the fuels needs to be cheap enough to compete with international prices.
Other		• Promote social acceptance of the projects using stakeholder and citizen involvement • Ensure education of workforce to carry out the development.

Table 23 – Overview of the roadmap (Skov and Mathiesen 2017; DTU et al. 2021)

11. What initiatives are needed to ensure successful integration of PtX?

To analyse which initiatives are needed to implement PtX on a large scale, five roadmaps have been analyzed. This approach was chosen to include different perspectives and understandings of what is needed for a development of PtX. Based on this, a list of suggestions for initiatives that can support the implementation has been gathered. The following will reflect on some of the initiatives found in the analysis of the roadmaps and reflect on the findings.

PtX is a highly energy demanding and costly process, the results of the energy system analysis made this clear, with the conclusion of a need for an expansion of 11,9 GW offshore wind and a cost of up to 226,5 Euro/ton CO2. There is a need for a massive expansion of RE as well as large investment sums to pay for the technology. This consideration seems to be overlooked in some of the plans. For instance, the roadmap made for IFD suggest blend standards with e-fuel for road transport, including light-duty transport. The argument for this is that it will create a demand, and thereby a market for methanol and that the conversion to electric cars is happening to slowly.(DTU et al. 2021) Based on the results from the energy system analysis and the fact that electric vehicles have a significant higher efficiency(Danish ministry of Climate, Energy and Utilities 2021), creating initiatives to speed up the for phase in of electric vehicles seem to be a more better solution. Further it should be noted that 6 GW of PtX can only cover 64 % of the fuel demand, excluding light-duty transport. Considering this, the cost, and the energy demand, I argue that the use of e-fuels should be prioritized to sectors without possibility for direct electrification.

Another suggestion which should considered is the recommendation for the hydrogen infrastructure. In the analysis of the plans and the political agreement, there is a broad agreement that a hydrogen infrastructure must be built to support the market for PtX, as the cheapest way of transporting hydrogen is assessed to be through pipelines. The question is, however, what need there will be to transport the hydrogen. The lack of knowledge of the future demand makes it a risky investment (IRENA 2022). Even with the assessment of pipelines being the cheapest way to transport hydrogen, it is a large investment to make. Further, the development of infrastructure projects has a long-time frame, both regarding planning and implementation. Energinet (n.d.) states that the framework for further developing a hydrogen grid in Denmark will not be finalized until 2023 and a hydrogen grid to Germany cannot be ready until 2030. (Energinet n.d.) Before expanding a large hydrogen network in Denmark, it is therefore recommended to map the need for a hydrogen grid.

Another perspective is the need for support. Based on the roadmaps there is a need for support, as the PtX cannot compete with fossil fuels on cost. It was found from the sensitivity analysis that from a socio-economic perspective it will be positive to implement PtX in a system with the current oil prices, as the implementation of PtX would not increase the system price and the carbon emission would be reduced. However, it is difficult to forecast the price development for the oil. Nevertheless, the market conditions need to support the desired development, regardless of the oil prices. To do so the actors suggest a lot of different solutions from blend standards increasing the demand to subsidies. Based on the analysis it cannot be assessed how to support the market. However, it is important to reflect on the desired development. For instance, re-warding flexible operation to integrate RE. Regulation of the tariffs is the first step towards that.

Research and development are important for continuously improve PtX, as PtX is assessed to be a key technology in the future energy system. The research and development should both fo-cus on the technologies, but also on developing the market. This also includes knowledge shar-ing between stake holders, as has been decided on in the political agreement to be managed by a PtX task force.

Based on this study, a number of overall lines and considerations have been found for the de-sign of future strategies. This study looks at the instruments in a broad perspective but does not go into the more precise design - In further studies, it must be investigated how the various in-struments must each be designed to support the development in the most sustainable way.

Lobbying for European regulation to push for a demand in the transport sector, also have down sides

In addition, PtX can be assessed on a European scale, since the systems are interconnected. This may also help to shed light on the issue of whether energy can add more value in other coun-tries.

12. Conclusion

This thesis aimed to answer the following research question:

What impact will 4-6 GW of PtX have on the Danish energy system and what initia-tives are necessary for it to be implemented successfully?

The implementation on 4-6 GW of PtX has been analyzed through an energy system analy-sis. The results shows that PtX is an expensive technology for the cost of the energy system, but also a technology with a great potential for reducing the carbon emissions. With the im-plementation of 6 GW of PtX the carbon emission from the system was reduced by 24%. The cost to achieve these saving is 227 Euro/ ton CO2.

PtX further has a large energy demand. When implementing 4-6 GW the need for RE will increase by 20-32 TWh RE/year, compared to the system without any PtX. If there is not enough RE capac-ity, the cost of the implementation will increase, further with small VE supply PtX can end up re-sulting in an increase in the carbon emission despite the reduction in oil consumption for transport.

Compared to the cost of achieving carbon reduction in other sectors PtX is an expensive solution, however, to reach carbon neutrality reductions need to be achieved in all sectors. As e-fuels are needed to reach carbon neutrality in the transport sector, the implementation is therefore necessary towards 2050. For the most cost-efficient reductions toward 2030, the cost should however be considered.

Based on this study, a number of overall lines and considerations have been found for the design of future strategies. This study looks at the instruments in a broad perspective but does not go into the more precise design - In further studies, it must be investigated how the various instruments must each be designed to support the development in the most sustainable way.

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Recommended initiatives/focus areas for a successful implementing of PtX:

Plan for the deployment of RE

- For PtX to produce green end fuels the electricity demand need to be covered by RE. In order to secure a sufficient amount of RE. A concrete plan for deployment of RE is needed.

Research and development:

- There is a need for further development and upscaling of PtX. Especially with the aim the decrease the price of the technology.
- The flexible operation of PtX also need to be supported by market mechanism. The market design could be developed based on learnings from demonstration plants testing different market conditions impact on the operation.
- Knowledge sharing is key when developing new technologies. The political agreement has decided on making a PtX taskforce.
- To ensure a workforce to facilitate the deployment is also an important initiative for the development.

Market regulation

- the market conditions need to support the desired development, creating good conditions for green technologies. For instance, it should be constructed to supports the integration of RE.
- To make PtX competitive with fossil fuels there is a need for economic regulation. This could consist of a CO_2 tax, subsidies or other types of regulation. The political agreement has already settled on changing the tariffs, which was one of the great barrier in the market.
- Another type of regulation is to promote an increase of the demand, it was suggested to do this changes in blend standard, tax reduction for 0-emission cars or travel taxes for aviation
- Another suggestion was to including the maritime transport and aviation as a part of the climate goal. to initiate the green transition in these sectors.

Infrastructure

- For infrastructure it is recommended to place PtX strategically – in cooperation with municipalities – and maybe involving stakeholders and citizen.
- Despite the agreement among the actor for a hydrogen grid. I believe the first step is assessing the need.

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14. Appendix 1: A forecast of Denmark's energy consumption for transport incl. International transport in 2030

Energy consumption/fuel All transport	2018 TWh	2025 TWh	2030 TWh
Petrol	15,81	14,08	12,01
Diesel	30,73	27,25	22,57
Jet-fuel fossil	12,28	12,54	13,13
Biogas	0,00	0,00	0,01
Bioethanol	0,75	0,67	0,57
Biodiesel	1,84	1,62	1,35
Bio-methanol	0,00	0,00	0,00
Bio-jetfuel	0,00	0,00	0,00
Syn-methanol	0,00	0,94	1,80
Syn-jetfuel	0,00	0,07	0,14
Electricity Train / bus	0,20	0,26	0,52
Electricity BEV + Plug-in-hybrid	0,03	1,11	2,41
Sum	61,64	58,50	54,41

15. Appendix 2 – Technology prices IDA2030

	Unit	MEUR pr unit	Lifetime (years)	O& M (% of inv.)
Electrolyser	MW-e	0,6	20	4
Hydrogen storage	GWh	7,6	25	2,5
JP synthesis	MW	9,37	25	4
Ammonia production	MW	0,87	20	2
Liquid Fuel synth	MW	0,5	25	4
Carbon recycling	Mt CO2	60	20	4
Wind offshore	MW	1,08	28	1,25

16. Appendix 2 data for sensitivity analysis:

Nuværende oliepriser https://energy.ec.europa.eu/data-and-analysis/weekly-oil-bulletin_en#price-developments :

Consumer prices of petroleum products net of duties and taxes In EURO			
	Euro-super 95 1000L	Gas oil 1000L	Fuel oil t
Denmark	1,138.54	1,221.89	1,057.87

Brændværdi / heating value:(Energistyrelsen 2021)

Fuel oil: 40,00 GJ/ton

Gas oil: 9,87 kWh/liter

Euro-super 95: 9,17 kWh/liter

Prices:

	Base scenarios	Sensitivity
Fuel oil (Euro/GJ)	10,4	26,44
Diesel gasoil (Euro/GJ)	15	34,4
Petrol/JP (Euro/GJ)	14,9	34,5

Fuel oil = 10,4 --> 26,44 Euro/GJ

Gas oil= 15--> 34,4 Euro/GJ

Euro Super= 14,9 --> 34,5 Euro/GJ

Wind:

Pris stiger med 20% (onshore=1,3 og offshore =2,44)