Danish PtX development pathways for 2030

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2. Problem area

In 2020 the Danish government decided to reduce national greenhouse gas emissions by 70. pct in 2030 compared to the baseline in 1990. Furthermore, to eliminate national greenhouse gases by 2050.

The transport sector is changing to renewable fuels. The market for electric vehicles is expanding, and more public transport has converted to use renewable energy. There are several solutions to make renewable fuels with the use of hydrogen made by electrolysis for the freight and shipping sector, but it needs an infrastructure that is not there yet. With renewable liquid fuels, fossil fuels can ultimately be substituted with the transport sector and the freight and shipping industry, where decarbonization by electrification is a challenge.

In Denmark, there are several projects regarding hydrogen production by electrolysis. The CEO of the organisation “Brintbranchen” Tejs Lauststen Jensen, says that in 2030 that should be produced 6 GW of green hydrogen in Denmark. There are different goals regarding the production of hydrogen in Denmark (Wittrup, 2020). The production goal of 6 GW is set by “Brintbranchen”. To reach the 70% goal for 2030, There is a need for 2-3 GW electrolysis capacity and 10-12 TWh PtX products, but the electricity used for the production should come from renewables (Brintbranchen, 2020).

Furthermore, there is a need for strategic planning to escalate the production further ultimately. Experts say the projects are valuable by themselves, but the projects should be larger (Wittrup, 2021). In table 1 are the goals from different sources shown.

Estimate	Provider	Source
2-3 GW (to cover 70%)	Klimapartnerskabet	Regeringens klimapartnerskaber (2021)
3 GW	Dansk Energi	Dansk Energi (2020)
6 GW	Analyse af potentialerne for storskala brint og PtX i Danmark. VE 2.0 Brint- og PtX-strategi.	Brintbranchen (2020)
Photovoltaic, 6421 MW Wind, 6154 MW Offshore Wind 5630 MW	Basisfremskrivning 2020 – Danmarks Klima- og Energifremskrivning	Danish Energy Agency (2020b)
Total CO2 emission from the danish energy system in 2030 11,7 Mt. (Complies with 2030 reduction target)	IDAs Klimasvar: Transport- og energiløsninger 2030	Lund et al. (2020)

Table 1: Targets and estimations for electrolysis capacity in 2030

The estimations in Table 1 show a need for strategic planning to find a possible solution for the future. The Danish parliament is saying that it is necessary to implement new technologies to reach the target.

"New tools and technologies are needed to meet the 70% target by 2030 and the goal of climate neutrality by 2050. The IPCC assesses, for example, that capture and storage are necessary to achieve the Paris Agreement's targets." (The Danish parliament, 2020;5)

If the national goal of decreasing the greenhouse gas emission with 70 pct. In 2030 must be reached within the energy sector has to be reduced from 30Mt to about 11,7 Mt GHG emission in 2030 (Lund et al.,2020). Electrolysis facilities are planning as new technologies could take part in getting the emissions from the transport sector down, and there are several new facilities in the pipeline. But due to investors perspective, the energy used for the production pathways are necessary to be from renewable sources. The projects are right now driven by the business case instead of focusing on how it fits the connected energy system (Wittrup, 2020). Companies see hydrogen as an investment in the future fuel and not focused on the national energy system and where the electricity comes from. Therefore, there is a need for a plan to integrate the electrolysis facilities into the existing energy system. Tejs Laustsen criticises the government for not planning to fabricate hydrogen as the neighbouring countries (Wittrup, 2020). The PtX sector needs to ensure enough green energy to produce before they upscale the production (Wittrup, 2020). Furthermore, the PtX plants should be built together with carbon capture facilities to utilize renewable fuels from carbon sources close by (The danish parliament, 2020).

To expand the production of renewable fuels, there must be enough green electricity from primary offshore wind in Denmark for the facilities to run entirely. As mentioned, there are contradicting meanings regarding hydrogen production because the industry sees hydrogen as a good business case instead of filling a demand. There are currently running 14 offshore wind power facilities in Denmark with a capacity of 1699 MW and more in the pipeline (Danish Energy Agency, nd). There are several electrolysis projects in the pipeline in Denmark. However, it is mentioned in Wittrup (2020) that the amount of wind power will still be a problem for future planning in relation to the production of renewable fuel. To see hydrogen as a business case can cause an adverse reaction to the energy system. The lack of offshore wind power will force hydrogen production to be supplied from non-renewable sources. Therefore, the fuels will no longer be handled as green (Energinet, 2019). Thus, the future wind power farms are crucial to implementing a green hydrogen production in Denmark, and the future expectations regarding the span from 2 GW to 6 GW predictions need to be elaborated to evaluate the Danish energy system and consider if it can sustain such a production of e-fuels to bring the GHG levels down. The whole procedure needs a development plan to make green fuels feasible. In table 2 below, the future and operating PtX plants are shown.

Project	**Capacity**	**Provider**	**Location**
Power2Met, Methanol	0,5 MW	Green Hydrogen Systems, Re:intergrate, AAU, E.ON, Nature Energy, Rockwool	Aalborg
Greenlab Skive, PtX Hydrogen and e-fuel	12 MW Phase II 250 MW	GreenLab,EuroWind, Everfuel, Eniig, E.ON, Energinet.	Skive
Large scale PtX in the municipality of Copenhagen	10 MW demonstration 250 MW Phase II 1,3 GW Phase III in 2030	Ørsted, CPH Lufthavne, Mærsk, DSV, SAS	Copenhagen
HySynergy, Green Hydrogen	20 MW + 500MWh (Storage) Phase I 1 GW Phase III in 2030	Shell, Everfuel	Fredericia
Energy Island, Bornholm	3-5 GW	50Hertz, Energinet	The Baltic Sea
Green Hydrogen Hub	350 MW + 0,2 GWh (Storage) 2025, 1 GW elektrolyse 2030	Eurowind, Core Energy, Energinet	Hobro/Viborg
Esbjerg Habour, Green ammonia	1 GW	Green Hydrogen, Siemens Gamesa, Copenhagen	Esbjerg

Table 2: Planned synthetic fuel and electrolysis plants in Denmark (DGC, 2020; CIP, 2021)

2.1 Problem formulation

Based on the problem area, there is a need for further strategic development on the targets for 2030. Therefore, the problem formulation is:

How can critical factors concerning PtX development pathways in the danish national energy system in 2030 be identified by simulating scenarios in EnergyPlan in relation to fulfilling the national CO2 reduction target of 70% in 2030?

To answer the problem formulation, three research question which will form the analysis are made. The research questions are:

Research question 1:

How can synthetic fuels be produced with CO2, N2 and H2 as feedstock and commercial TRL throughout the whole supply chain?

Research question 2:
What are the essential critical factors to Danish PtX-development pathways, and how are they identified and assessed by simulating technical national energy system analysis?

Research question 3:
How can the optimum hydrogen storage crucial to Danish PtX-development pathways be calculated concerning biomass consumption and the system's total cost?

The questions above are important because they define several parts of the problem formulation and give a reasonable basis for answering the fullest.

2.2 Limitation

In answering the research questions, it is necessary to limit the research within the given time for the project. There has been some limitation within the subject field that will not be discussed further. In the following section, the different field subjects mentioned are not included in the study and what priorities are made regarding the technology.

2.2.1 Synthesis

Ammonia steam reforming,

Due to high CO2 emissions, hydrogen produced by steam reforming is not taken into account because it has a large CO2 emission. The quote is taken from the Danish Energy Agency (2021, P 273-274).

”The hydrogen is predominantly produced by steam reforming of natural gas (methane), a process that results in large emissions of fossil CO2. Thus, reducing the CO2 103 Green Ammonia emissions from ammonia production is heavily linked to reducing emissions from hydrogen production.”

Electrochemical synthesis of ammonia – green NH3,

Because of the lower TRL level, this technology is not described further. Quote from the Danish Energy Agency (2021, P 276)

“Direct production of NH_3 by electrocatalytic reaction of water and air, i.e. eliminating the Haber-Bosch process, may become an alternative process for green NH_3 with use of renewable electricity. This technology is still only at the research level.”

Conventional – grey NH3,

This technology is not mentioned further in the report because of fossil fuel or plant-based reformers quotes from the Danish Energy Agency (2021, P 274).

“A conventional ammonia plant uses fossil fuels (in most cases natural gas) as its raw material.”

“conventional NH_3 plant based on primary and secondary reformer technology, where nitrogen is admitted via air to the secondary reformer. Alternative reformer configuration is autothermal reformer (ATR) or single steam methane reformer (SMR) combined with ASU unit to provide the nitrogen.”

Conventional – blue NH_3,

This technology will reduce the CO2 emissions of the conventional grey NH3 by using carbon capture, but the material used is natural gas. Therefore, this technology is not included in the research.

“A blue ammonia plant is a conventional NH3 plant with carbon capture (CC) to capture the CO_2 emissions from the reformer. This will significantly reduce the carbon footprint compared to that of grey ammonia. However, the raw material is still natural gas, and the plant layout is similar to that of a conventional plant.” (Danish Energy Agency, 2021 P 275)

2.2.2 Carbon capture processes

Amine-based carbon capture technology is used in this study because of the availability and TRL high TRL level.

“Amine based CC technology is the more mature and more widely demonstrated CO_2 capture technology available today” (Danish Energy Agency and Energinet, 2020, P 102)

Chilled ammonia/carbonate process,

Due to slow reaction times and unfavourable conditions that will limit the application of this technology, it is not mentioned further in the study.

“Chilled ammonia (or ammonium carbonate process) technology is relatively similar to amine CC process except that a solution of ammonium carbonate is used instead of amine.” (Danish Energy Agency and Energinet, 2020 P134)

“However, the prolonged reaction kinetics and unfavourable equilibrium conditions will limit the application of this process to high-pressure gas streams hence it is not suitable for CO_2 capture from flue gas.” (Danish Energy Agency and Energinet, 2020 P134)

Other Post-combustion processes,

Because of the relative low TRL, other alternative post-combustion processes will not be further described in the study.

"The aim with these alternative solvents is to achieve lower energy consumption and reduce the cost of CC technology. Most of the processes involving more novel solvents have not been demonstrated at large scale and are thus at relatively low TRL" (Danish Energy Agency and Energinet, 2020 P134-135)

Solid sorbent,

Solid sorbet used in post-combustion has a low TRL level and, therefore, not integrated further in the research. Furthermore, it is mentioned that it is not relevant for a project in the near future.

"Post-combustion processes with the use of solid sorbents instead of liquid solvents are under early-stage development." (Danish Energy Agency and Energinet, 2020 P 135)

"Solid sorbent technology is at low TRL and not relevant for near or midterm retrofit projects." (Danish Energy Agency and Energinet, 2020 P 135)

Cryogenic separation of CO2,

Separation of CO2 with the use of freezing out CO2 from flue gas has potential, but it is not mentioned further in the study due to low TRL.

"Processes for CO_2 capture by freezing out CO_2 from the flue gas, i.e. cryogenic separation, are also under development." (Danish Energy Agency and Energinet, 2020 P 135)

"The technology may have some potential but is regarded as low TRL with only relatively small-scale pilot plant trials conducted." (Danish Energy Agency and Energinet, 2020 P 135)

Direct air capture,

To capture CO2 directly from the air is a technology only demonstrated on a pilot or small scale, and therefore, it is not used in the study.

“The Direct Air Capture (DAC) technology captures CO_2 from ambient air and recovers a concentrated CO_2 stream like other CC technologies… Most of the technologies and methods for DAC are still being developed in the laboratory and are thus low TRL. A few technologies have been demonstrated in the pilot- and/or commercial plants, but at relatively small scale (up to a few tonnes per day).” (Danish Energy Agency and Energinet, 2020 P 136)

2.2.3 Electrolysis processes

Alkaline Electrolysis Cell (AEC) is the electrolysis technology with the highest level of TRL and, therefore, used to describe the production pathways in this study. In the following section, electrolysis technologies with lower TRL level mentioned.

SOEC,

For solid oxide electrolysis, the difference from AEC is that the electrolyte is an oxide ion solid-phase component. Commonly yttria-stabilized zirconia is used both on the anode and the cathode. The cathode is made of nickel and yttria-stabilized zirconia for hydrogen generation. The anode is made of a mix of conductors with ionic-electronic capabilities and yttria-stabilized zirconia. With the SOEC electrolysis, the oxygen is travelling through the solid electrolyte. The SOEC can convert both steam and CO2 at the same time and therefore have the possibility to generate syngas. In figure X, the SOEC electrolysis is shown (Danish energy agency, 2021).

Reaction in the cathode: $H2O + 2e - \longrightarrow H2 + O\ 2-$

Reaction in the anode: $2O\ 2- \rightarrow O2 + 4e$-

PEM,

For PEM electrolysis, typically, the membranes are catalyst coated; it could be a mesh of metal, carbon, or other metallic material. The membrane is made of perfluorosulfonic acid, which makes the proton exchange polymer electrolyte membrane. In PEM, water is added to the anode side, and it is the H+ ions travelling through the membrane to the cathode where hydrogen is extracted. Facilities that use PEM commercially use platinum and iridium oxide for the electrodes. Platinum for the cathode and iridium oxide for the anode (Danish energy agency, 2021). In figure x, below is the reaction and a model of a PEM electrolyzer shown.

Reaction in the cathode: 2H+ + 2e- → H2

Reaction in the anode: H2O → 12 O2 + 2e - + 2H+

Parameter	**PEM**	**SOEC**
Electrolyte	Polymer membrane	Yttria stabilized zirconia (YSZ)
Anode	Pt, Pt-Pd	Ni/YSZ
Cathode	RuO_2, IrO_2	LSM/YSZ
Maturity of technology	Commercial (TRL6-8)	Demonstration (TRL 5)
Cold start-up time	5-10 minutes	680-880 minutes
Pressure	1 bar	3 bar
Operating temperature	25°C	150°C
Input	Water and electricity	Water, electricity and heat
Hydrogen purity	99,99	99,9
Efficiency	67-82 %	100 %
Lifespan	25.000-50.000	20.000

Table 3: Electrolysis comparison of SOEC and PEM

(Danish Energy Agency, 2021; Schmidt et al., 2017; Pinsky et al., 2020)

3. Theoretical framework

In this chapter, the theories used to create the framework of the study describes. Furthermore, the application for chosen theories is mentioned concerning the topic of synthetic fuels.

3.1 Pathway theory

Daniel Sperling (1984) presented different ways for planners and decision-makers to analyze and evaluate different pathways for technological development. Planners and decision-makers sometimes have little to no clue about a particular technology. The processes that need to be taken into account and the *pathway theory* make it possible with given factors to elaborate on different options regarding technical development (Sperling, 1984). Typical analysts present technological choices as an end state. Still, Daniel Sperling (1984) explains that the end state is not very useful to society and planners since the steps that must be taken and avoided to reach that end-state are missing. (Sperling, 1984). This stresses the need to analyse the road ahead to reach a desirable end-state, and therefore which steps must be taken or avoided.

Daniel Sperling (1984) presents different approaches to end state planning of transition pathways. The deficiency of conventional economic and technical analysis is a factor for using a pathway approach because financial and technical criteria are crucial from the investor and planners perspective (Sperling, 1984). An example of the use of *pathway theory* is presented by Daniel Sperling (1984), where he is studying different paths of renewable liquid fuels options for the transport sector. In that regard, the theory suggests that the analytical framework should be designed after critical factors that emphasise adopting a given pathway. Daniel Sperling uses renewable fuels as an example to describe *pathway theory*. In this case, decarbonisation and climate adaptation would be the values and beliefs, and the critical factors would be energy density, production price, feedstock, volume and resource availability.

Furthermore, he has focused on the potential reduction of GHG and sustainability regarding the current and future demand (Sperling, 1984). This is necessary to plan the future to analyze the road ahead while using the end-state as the goal to generate a specific transition pathway (Sperling, 1984). The theoretical framework may be extended and applied in two ways; "*for explanatory analysis of the determinants of technological change, and for normative analysis to help the government guide the process of change*" (Sperling, 1984; 343).

In this report, the theoretical framework of pathway theory is applied by analysing the future energy system and determining a technological change and elaborate on the goals for hydrogen production. In the section of transition theory in the *pathway theory*, there are four significant features included where the critical factors are exemplified. The four major features are described in the following sections.

3.1.1 Values and beliefs

Through the explanation from Daniel Sperling (1984), values and beliefs are associated with environmental, technical, or economic feasibility (Sperling, (1984). By mapping the different actors and activities, the pathway of ‘who to do what at what moment’ can be specified to implement a certain technology. The level of technical analysis must be taken into account to develop the pathway to analyze the economic feasibility through the path to the end-state.

3.1.2 Identifying the critical factors

Critical factors are the factors that influence the technological development path with both negative and positive affect. Critical factors are usually identified with factors that refer to interactions and relations between systems concerning the pathway theory. That could be institutions managing and operating the technologies, performance, cost, and resources available (Sperling, 1984). Furthermore, it is necessary to see what purpose the different actors are working after. Concerning hydrogen production in Denmark, it is essential to differentiate between the goals from the government and the goals from the industry because there could be contradicting purposes related to the production goals. The critical factors connected to the planning could be regulatory statutes, change in the physical environment, and other competing technologies (Sperling, 1984).

3.1.3 Critical factors specified in representative settings

In this part, the location makes the differences between the factors. Concerning hydrogen production, the facility's location changes critical factors regarding the dependency of valuable resources that can force a change to the price due to demanding the same resources as a facility with more resources available (Sperling, 1984). Therefore, it is necessary to plan out suitable locations for severe technology. The analysis will show where it is attractive and unattractive to place a technology (Sperling, 1984).

3.1 4 Temporally changes specified for critical factors

Technology changes over time; temporally, changes are something to consider when planning towards an end-state goal. The technology pathway should be examined within their working environment and not around anything else to secure the most specified analysis. Concerning the critical factors, it is essential to revisit the analysis to make a suitable projection through the process (Sperling, 1984).

3.1.5 Purpose and application

In this report, critical factors should be identified to make a projection about the future energy system and how the end-state goals of hydrogen production given by the different actors mentioned (Scope 2.) will fit in the future. The critical factors will show the possibilities and obstacles regarding the planning towards the goal for 2030.

3.2 Choice awareness theory

This section will describe the theoretical theses of the report. The Choice Awareness Theses evolves around the perception that institutions, organizations, and individuals value things differently. Strategies and interest differentiate from one another, as decision-makers tend to reinforce their interest in their development strategies. The Choice awareness theses acknowledge that the conditions mentioned above often lead to a situation of no choice. (Lund, 2015) The concept of no choice arises from the perception that organizations and decision-makers tend to eliminate choices from the decision-making process that do not correspond or comply with their interest. E.g., could be profit maximization or process optimization. (Lund, 2015) To counteract the development of no-choice strategies, the theory advocates three different approaches: technological alternatives, feasibility studies based on institutional economic thinking, and design of public regulation measures of conflicting interest and changes in the democratic decision-making infrastructure. (Lund, 2015) The report seeks to design technological alternatives or scenarios to the current development path or strategy proposed by governmental institutions and organizations presented in the reports problem area. These designs will be performed by modelling the danish energy system in contrast to the proposed extensions of the system proposed in the problem area. The different designs will be assessed by performing minor feasibility studies on each development path. (Lund, 2015)

3.2.1 The true and false choice

The Choice Awareness Theses distinguish between two definitions of choices which are conceptualized as the true choice and the false choice. The theory advocates that decision-makers always should be presented with true choices, a choice between two or more real options. (Lund, 2015) False choice occurs when decision-makers must base their determination on one apparent choice, which is no choice. So basically, if there is only one real or viable option to a decision or strategy, there is no choice but only one viable approach. In this situation, the theory suggests that technological alternatives and feasibility studies should be designed to enlighten decision-makers of other true choices. (Lund, 2015)

3.2.2 The theses

The choice Awareness thesis can be separated into two minor theses. The first addresses the societal level. The second addresses a situation where society wants to implement a strategy that implies radical technological changes. (Lund, 2015) At the societal level, when society wants to implement strategies, the interest and discourse of the organization and decision-makers will influence the strategy, which ultimately hinders the development of new radical choices and therefore eliminates certain alternatives. (Lund, 2015) The perception is that the societal level creates the perception that there is no choice but to implement the proposed strategy that will reinforce the current interest and discourse of the organization and decision-maker. The acknowledgement is based on the neoclassical economics theory, which states that existing institutions and technological setup are regulated by the free market, which by definition will identify and implement the best solutions in the face of competition. (Lund, 2015) But as the theses emphasize, this will result in the exclusion of strategic alternatives, technical evaluation of new technologies that comply with requirements, and lastly, the design of feasibility studies that not only aims for economic feasibility and therefore only cost-effective technologies. Therefore, the core element of the theory is to raise awareness of other feasible alternatives or choices to decision-makers. (Lund, 2015) The second theses evolve around the perception that society will benefit from raising awareness of other alternatives. The thesis argues that feasibility studies should be designed to analyze other types of feasibility than what is economically feasible. E.g., Social and environmentally feasibility. Together, economic, social, and environmental feasibility is conceptualized as socio-economic feasibility. (Lund, 2015)

3.2.3 Purpose and application in the report

The report relates to both theses, the acknowledgement of the impact a strategy can have on the societal level and the need to raise awareness to other choices or strategies. Additionally, the report recognizes the need for socio-economic feasibility studies to present estimated impacts of alternate technological development paths and strategies. The aim is to raise awareness of several national development paths that either comply or contribute to the Danish national target of 70 pct. CO2 reduction in 2030 by performing minor socio-economic feasibility studies on each scenario or development path presented in the problem area.

4. Methodological framework

In this chapter, the methodological framework of the report described. The study's methodological framework consists of two methods, a Socio-economic feasibility study and a national energy system analysis.

4.1 Socio-economic feasibility study

To analyse the consequences of alternate technological development paths, minor socio-economic feasibility studies on the proposed strategies and development paths presented in the reports problem area will be carried out. The aim is to raise awareness of the national development pathways that contribute to or comply with the danish national target of 70 pct. CO2 reduction in 2030. According to Hvelplund and Lund 1998, socio-economic feasibility studies can be performed by designing feasible technical alternatives and evaluating those alternatives' social, environmental, and economic cost. (Hvelplund and Lund, 1998) Feasibility studies can be designed either as a socio-economic feasibility study or as a public regulation study. The two methods can be distinguished in how alternate development paths are designed and how socio-economic analyses of those paths and strategies are carried out.

The table (Table 4) below illustrates how the two methods can be carried out as well as how they differ. (Hvelplund and Lund, 1998)

Table 4.

Methodological approach	Design of alternate technological development paths	Socioeconomic analysis of alternatives
Socio-economic feasibility study	Modelling of technical scenarios and technical alternatives	Identification of the best solution from an analysis of economic, environmental, political, and social feasibility
Public regulation study	Implementation strategies of scenarios and alternatives	The design of an implementation strategy relies on results from an analysis of economic, environmental, political and social feasibility.

Table 4: Feasibility study and public regulation study Source: Hvelplund and Lund, (1998)

Feasibility studies can, in general, be separated into two steps. Step 1 involves defining what should be studied (development paths), for whom it should be studied, and why it should be studied. Step 2 encompasses the design of how the study should be carried out. The precedence here is The Diamond-E-analysis. (Hvelplund and Lund, 1998). As mentioned before, the report will perform a socio-economic feasibility study of proposed development paths. The most distinguishable feature of a business-economic feasibility study is the exclusion of environmental cost and employment effects. According to Hvelplund and Lund, feasibility studies carried out for governmental institutions should be carried out as socioeconomic feasibility studies that include the socio-economic goals of society. Thought they also emphasize that business economic studies must be included as well. *"Concludingly it is emphasized that both business – and socioeconomic feasibility studies should be elaborated by both governmental institutions and private organisations." (Hvelplund and Lund, 1998;25)*

4.1.1 WWW Framework

The study of what, for whom, and why the feasibility study designed. What should be studied or the aim of the study can range from single project analyses to modelling of energy system analyses. For whom the study is designed for, or for whom is the project feasible, refers to the self-interest and discourse of whom the feasibility study is made for. The definition and priority of when or at which point something is feasible will range from study to study according to whom the study is designed for, and in extension, why is the study designed. (Hvelplund and Lund, 1998)'

What,

The report is a feasibility study that aims to identify critical factors crucial to proposed hydrogen and synthetic fuel production pathways by several organizations. Further, the aim is to define how the Danish energy system can comply with its respective portion of the Danish national 70% CO2 reduction target in 2030.

Whom,

The study is performed to equip planners and decision-makers with the necessary critical factors to determine or plan further studies or strategic pathways. Since the Danish government still lacks a plan for which role hydrogen production and utilization will have to perform in the fulfilment of the 2030 target, this report is also written to the Danish government and partner organizations.

Why,

The report and study are set up to create multiple pathways for hydrogen production and utilization as an addition or input to the current planning of the Danish hydrogen strategy, which is supposed to be published in 2021.

4.3 National energy system analysis

This section will describe the reports primary methodology and how it will be applied as an analytical framework and tool. EnergyPLAN is a software program that enables users to model energy systems for analysis. The outcomes of EnergyPLAN system analysis array from technical to market-economical simulations strategies of the consequences and opportunities the implementation of different energy systems and investments encompasses on a national and regional level. (Lund 2015; Lund & Thellufsen 2020) As a tool, EnergyPLAN can assist its users in the planning of national and regional energy system strategies. The program includes various energy-producing and consuming technologies, which together define the energy grid. The technologies range from boilers, combined heat and power-producing plants, heat pumps, fluctuating renewable energy sources and technologies (wind, solar, hydro), biomass conversion technologies (biogas, thermal hydrolysis), power to x conversion technologies (ammonia, hydrogen, methane, methanol), and storage options as batteries, compressed air, synthetic fuels, and vehicle to grid. (Lund 2015; Lund & Thellufsen 2020)

The different technologies in the model define the energy system and interact on a cross-sectoral scale. Production of and demand for electricity, gas, district heating, and cooling are entangled. (Lund 2015; Lund & Thellufsen 2020) Synergy in the whole energy system is necessary to comply with energy demands. As a methodology, the program is a deterministic in- and output model, where the user defines the inputs as production and demand of energy which includes capacity and efficiency rates. The outputs of the program are a calculated energy balance and cost of the system. Presented in annual, monthly, and hourly production and energy consumption, import and export of electricity, production of excess electricity, and total cost of the investment strategy, the total cost includes fuel cost, taxes, variable and fixed operational cost and direct investment cost. (Lund 2015; Lund & Thellufsen 2020) *"The EnergyPLAN model can be used to calculate the consequences of operating a given energy system in such a way that it meets the set of energy demands of a given year. Different operation strategies can be analyzed" (Henrik Lund 2015; 68).* The program differentiates between two types of simulations strategies. The aim is either technical regulation of an existing national energy system or market-economic regulations where profit optimization is the aim of analysis. (Lund, 2015)

4.3.1 Energy system analysis methodologies

There are three types of energy system analysis, technical analysis, market-exchange analysis, and feasibility studies. The technical analysis encompasses the modelling of national and regional complex energy systems and the simulation of different technical regulation strategies. The given outputs of technical analysis are typically annual energy balances, fuel consumptions and CO2 emissions. (Lund & Thellufsen, 2020) The second type of methodology is the market exchange analysis involving trade and exchange on international electricity markets. This method aims to identify prices on the market and determine the consequences of changes in import and export has to the spot price.

Furthermore, this type of energy system analysis is also applied to determine the production cost of individual electricity-producing components of the energy system targeted. (Lund & Thellufsen, 2020) The market exchange simulations strategy does only include variable cost. The last and third methodology is feasibility studies. The study and methodology aim to calculate feasibility as the total annual cost of the targeted energy design and strategy. The study encompasses the socio-economic consequences of the system and includes inputs as investment cost, fixed and variable operational cost, lifetime periods, and interest rates. This type of analysis results is the total cost of the simulated energy system or strategy, which are presented as fuel cost, fixed and variable investment cost, direct investment cost, electricity exchange cost, and income. (Lund & Thellufsen, 2020)

4.3.2 Overall structure of energy system analysis and methodology

The overall input structure of data in EnergyPLAN covers energy demands, energy production, cost, and simulation (regulation, operation, and technical limitations of the system). The procedure of simulating energy systems in EnergyPLAN is shown in the table beneath. The procedure involves four steps, where the third step can be divided into either a Technical Energy System Simulation or a Market-Economic Energy System Simulation. Thus, it’s possible to do both calculations or simulations since it’s only a matter of changing the output model in the software. (Henrik Lund, 2015) In broad terms, proceeding with the Technical Energy System Simulation can result in outputs that identify the least fuel and CO2 consuming system. On the other hand, the Market-Economic Energy System Simulation aims to determine which system or simulation is the least cost consuming. (Lund & Thellufsen, 2020)

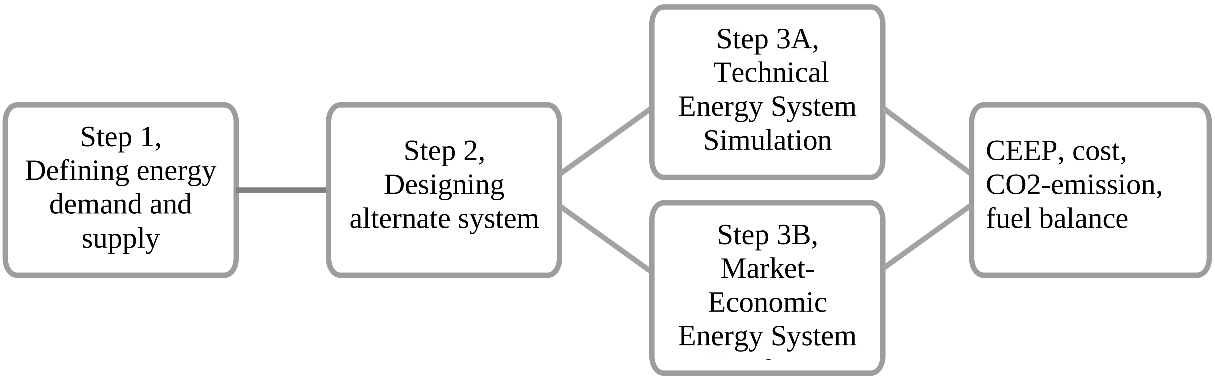

Figure 1: Illustration of the EnergyPlan analysis Source: Lund 2015

4.3.3 National energy system analysis

Step 1, Defining reference energy supply and demands.

The first step of a national energy system analysis is to define the reference energy demand, which is defined as the annual electricity demand of the system, given in the TWh/year. In extension, it is necessary to choose an hourly distribution that resembles the national and local distribution and utilization of electricity in the system. (Henrik Lund, 2015) The same procedure must be carried out for the heating demand (district heating and individual heating) in the system, and here it is also necessary to choose a distribution dataset. In addition, fuel demand and transport demands have to be included to resemble the whole energy system. If the system has storage capacities, these need to be included in this step too. (Henrik Lund, 2015) When defining the reference energy supply, the energy supply and the consumption of fuels based on average annual consumption must be divided between the different energy sources and production technologies. In addition, must the capacities and efficiencies of the single production units be defined. Distribution data sets must be included for intermittent energy-producing and consuming components in the system. (Henrik Lund, 2015)

The reference supply and demand applied in the report’s simulation is based upon two reference models created by the author's Peter Sorknæs and Jakob Zinck Thellufsen. In 2019 Peter Sorknæs designed the DK 2020 model built upon the Danish energy agency’s Energy and Climate Outlook 2018. The model is designed to resemble the Danish energy systems demand and supply of energy in 2020. The model inputs can be divided into the following groups listed in the table below. The exact numeric modifications are illustrated in the article CORE – Coordinated operation of integrated energy systems, WP1. (Sorknæs 2019) The DK 2030 model designed by Jakob Zinck Thellufsen is a design of the Danish energy systems demand and supply in 2030 based on projections of today’s energy system to 2030. The projections are made by the Danish energy agency and presented in the report Basisfremskrivninger 2018 (The Danish Energy Agency, 2018). The DK 2030 model is built upon the DK 2020 model with the projections made by the Danish energy agency. In addition to the projected supply and demand, the purpose of designing the model was to modify or adjust the energy system 2030 so that it corresponds with the national target of 70% CO2 reduction in 2030. One main difference between the two models is the transmission line which in the DK 2020 Model has a capacity of 7105 MW (Sorknæs 2019), where the transmission line is eliminated in the DK2030 model. This means that electricity can is exported neither imported. This is mainly done due to the projections in the system. To make the system respond to the modelling which has been made, the transmission line had to be eliminated so that the required electricity demand in the system not only is imported to compensate. The critical excess electricity production or CEEP states how much excess electricity the system produces. So in the DK 2020 model, the CEEP is merely 0 TWh, and in the DK 2030 model, the CEEP is 3,16 TWh. (Lund et al. 2020) The main aim of the DK 2030 model is to design an energy system that meets the CO2 reduction required by the energy system to comply with the national 2030 target. As mentioned in the problem field, the energy system's total emissions must be reduced to 11.7 Mt or less to meet the reduction percentage for which the energy system is responsible for achieving the 2030 target. (Lund et al. 2020) The main adjustments or modifications performed in the DK 2030 model is divided into the following main groups presented in the table below. The exact numeric changes can be seen in the report's appendix. In the table below is a comparison of the core model of 2020 and the 2030 strategy from IDA shown,

DK 2020 Model (CORE)	DK 2030 Model (IDA Strategy for 70% CO2 reduction in 2030)
Electricity production	Expansion of the renewable energy supply capacity
District heating	Optimized energy efficiencies for buildings
Central heating	Optimized electrical efficiencies in heat pumps, district heating, and cooling.
Cooling	Overall electrical savings in the total electricity demand.
Fuel distribution and consumption	Elimination of Coal power plants
Transport fuel demands	Substitution of individual heating with natural gas to heat pumps
Waste incineration	Substitution of petrol and diesel cars to public transport
Individual heating	Substitution of petrol cars and motorbikes and diesel cars to electric and plug-in cars.

Biogas production	Substitution of fossil fuel usages in cars, ships, and aeroplanes with the synthetic fuels, DME, Methanol, Ammonia, and Jet Fuel
Exchange of electricity	Expansion of the biogas production
Distribution hours for supply and demand, based on production and consumption in Denmark 2015.	Introduced electrolysis supply and storage of hydrogen

Table 5: Comparison and description of both the 2020 model and IDA’s 2030 model

The table below shows the difference between the two reference scenarios, the DK 2020 and DK 2030 models. To test and simulate different hydrogen scenarios in 2030, it is necessary to create a new reference scenario based on the DK 2030 model, as the model has already introduced electrolysis and synthetic fuels into the system. The report's reference scenario will contain the same supply and demand as the DK 2030 model is projected to, but hydrogen production and storage will be reset, and the synthetic fuels introduced to the system will be converted back into fossil fuels. Furthermore, efficiencies and cost for both hydrogen production and synthesis to fuels have been updated, so it matches the cost and efficiencies of the proposed pathway in the reports first analysis. These changes or adjustments to the model can be seen in the appendix. In the modelling of scenarios in the analysis and the reports reference system 2030, the CEEP on 3,16 from the DK 2030 model is held so that all the scenarios and models have the same theoretical proven CEEP. The difference between the DK 2020 model, DK 2030 model, and the reference designed for the report is illustrated in table 6 below.

Energy model	DK 2020 Model (Sorknæs, 2019)	DK 2030 Model, IDA Strategy for 70% CO2 reduction in 2030. (Thellufsen, 2021)	**Reference system 2030**
Electrolysis capacity, MW	0	1223	0
Fossil fuels in transport, TWh/year	Jet Fuel 0,36. Diesel 30,77. Petrol 14,83.	Jet Fuel, 0,3 Diesel, 18,5 Petrol 9,5	Jet Fuel, 0,31 Diesel, 21,48 Petrol 9,5
Synthetic fuels in transport, TWh/year	0	DME/methanol 2,82 Ammonia 0,16 Jetfuel 0,01	0
CO2 Emissions (Mt)	29,76	11,58	12,31
Excess heat from electrolyser (TWh/year)	0	0,16	0
CEEP	0	3,16	3,16

COST (MEUR)	Total variable cost 7792, Fixed operation cost 3694, Annual investment cost 9606, Total Annual cost 21092	Total variable cost 3383, Fixed operation cost 3649, Annual investment cost 14676, Total Annual cost 21708	Total variable cost 3611, Fixed operation cost 3544, Annual investment cost 14430, Total Annual cost 21579
Renewable energy capacity	Photovoltaic, 952 MW Wind, 4232 MW Offshore Wind, 2051	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 6630 MW Wave 132 MW	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 5135 MW Wave 132 MW
Electrolyser electricity consumption in TWh	0	5,56	0
Fuel balance in TWh	Coal 19,85. Oil 66,57. N. Gas 25,65. Biomass 59,68 Renewable 21,20	Coal 0,95. Oil 32,90. N. Gas 11,86. Biomass 37,42. Renewable 55,68.	Coal 0,95. Oil 35,89. N. Gas 11,46. Biomass 39,31 Renewable 49,00

Table 6: Data from 2020, IDA's 2030 and self-designed 2030 system

Step 2, Defining the regulation of the energy supply system.

In this step, the simulation regulation strategy must be defined, and this is done by applying predefined general strategies and limitations present in EnergyPLAN. The two regulation strategies are the technical-, and market-economic optimization of the energy system. (Henrik Lund, 2015) As mentioned earlier and visualised in figure 1, the analyst can choose between Technical Energy System Simulation or a Market-Economic Energy System Simulation. This can be done by changing the regulation or simulation strategy of the energy system. The report will perform the technical simulation. If the technical simulation is chosen, the analyst must define which of the following four regulation strategies the system's simulation will prioritise. (Lund & Thellufsen, 2020)

1. Balancing heat demands
2. Balancing both heat and electricity demands
3. Balancing both heat and electricity demands, reducing CHP when needed to maintain grid stabilisation
4. Balancing heat demands applying the triple tariff

The chosen regulation strategy for the report’s technical analysis is the second regulation strategy, where both heat and electricity demands are balanced.

Step 3, Defining alternatives

Alternative systems can proceed when the definition of the systems reference energy supply and demand and the choice of simulation and regulations strategy has been analyzed. The EnergyPLAN software can calculate the output in a matter of seconds, so in this step, the analyst can run different scenarios, strategies, and different regulations (Lund, 2015). The proposed scenarios or alternatives are illustrated in the tables below in section 4.3.4. The results will be presented in the reports second analysis.

4.3.4 Pathways or scenarios

4.3.5 Identifying critical factors,

The following pathways will be built upon the reports reference system 2030, and the results will be presented in the reports second analysis.

Scenario (1), BF20

Based on,

Photovoltaic, 6421 MW Wind, 6154 MW Offshore Wind 5630 MW	Basisfremskrivning 2020 – Danmarks Klima- og Energifremskrivning	(The Danish Energy Agency 2020b)

Table 7: Scenario 1 and sources

Electrolysis capacity, MW	Synthetic fuels, PJ	Total CO2 Emissions in Mt	Excess heat in TWh	CEEP in TWh	COST in MEURO	Renewable energy capacity in TWh	Electrolysis electricity consumption in TWh	Fuel balance in TWh
-	-	-	-	-	-	Photovoltaic, 6421 MW Wind, 6154 MW Offshore Wind 5630 MW,		

Table 8: Critical factors and the data used for the analysis of Scenario 1

Scenario (2-3), 2000-2500 MW Electrolysis,

Based on,

2-3 GW (to cover 70%)	Klimapartnerskabet	Regeringens klimapartnerskaber (2021)

Table 9: Scenario 2 and sources

Electrolysis capacity, MW	Synthetic fuels, PJ	Total CO2 Emissions in Mt	Excess heat in TWh	CEEP in TWh	COST in MEURO	Renewable energy capacity in TWh	Electrolyser electricity consumption in TWh	Fuel balance in TWh
2000-2500 MW	-	-	-	-	-	-		

Table 10: Start point of Scenario 2

Scenario (4), 3000 MW

Based on,

2-3 GW (to cover 70%)	**Klimapartnerskabet**	**Regeringens klimapartnerskaber (2021)**
1,4 PJ, Domestic aviation 8 PJ, Domestic shipping	IDAs Klimasvar: Transport- og energiløsninger 2030	Aalborg Universitet and IDA (2020)

Table 11: Scenario 4 and sources

Electrolysis capacity, MW	Synthetic fuels, PJ	Total CO2 Emissions in Mt	Excess heat in TWh	CEEP in TWh	COST in MEURO	Renewable energy capacity in TWh	Electrolyser electricity consumption in TWh	Fuel balance in TWh
2000-3000 MW	1,4 PJ. Jet fuel 8 PJ, ammonia	-	-	-	-	-	-	-

Table 12: Start point of Scenario 4

4.3.6 Calculating the optimum of hydrogen storage,

Scenario (5), 4000 MW

Based on,

Scenario 2	2000 MW Electrolysis

Table 13: Scenario 5 and sources

Electrolysis capacity, MW	Synthetic fuels, PJ	Total CO2 Emissions in Mt	CEEP in TWh	COST in MEURO	Renewable energy capacity in TWh	Electrolyser electricity consumption in TWh	Fuel balance in TWh	Hydrogen Storage Capacity in GWh
4000 MW	-	-	-	-	-	-	-	-

Table 14: Start point of Scenario 5

Scenario (6), 5000 MW - Domestic aviation and shipping

Based on,

Scenario 3	2500 MW Electrolysis

Table 15: Scenario 6 and sources

Electrolysis capacity, MW	Synthetic fuels, PJ	Total CO2 Emissions in Mt	CEEP in TWh	COST in MEURO	Renewable energy capacity in TWh	Electrolysis electricity consumption in TWh	Fuel balance in TWh	Hydrogen Storage Capacity in GWh
5000 MW	1,4 PJ. Jet fuel 8 PJ, ammonia	-	-	-	-	-	-	-

Table 16: Start point of Scenario 6

Scenario (7), 6000 MW - Domestic aviation and shipping

Based on Scenario 4 and,

6 GW	Analyse af potentialerne for storskala brint og PtX i Danmark. VE 2.0 Brint- og PtX-strategi.	Brintbranchen (2020)
1,4 PJ, Domestic aviation 8 PJ, Domestic shipping	IDAs Klimasvar: Transport- og energiløsninger 2030	Aalborg Universitet and IDA (2020)

Table 17: Scenario 7 and sources

Electrolysis capacity, MW	Synthetic fuels, PJ	Total CO2 Emissions in Mt	CEEP in TWh	COST in MEURO	Renewable energy capacity	Electrolyser electricity consumption in TWh	Fuel balance in TWh	Hydrogen Storage Capacity in GWh
6000 MW	1,4 PJ. Jet fuel 8 PJ, ammonia	-	-	-	-	-	-	-

Table 18: Start point of Scenario 7

5. State of the art

This chapter will present state of the art concepts concerning energy systems and technology readiness level. Further, the chapter describes current and future EU legislation regarding hydrogen production and utilization.

5.1 A fluctuating energy system/Smart renewable energy systems

Electrolysis and production of e-fuels are not relevant when the energy is not from renewable sources. Therefore, a fluctuating energy system is needed to supply the electricity required for production. As mentioned in the scope, the excess electricity production from the future wind power farms should supply the electrolysis facilities. Concerning a Smart Energy System, a cross-sectoral approach connecting the energy system is needed to benefit every part of the system (Lund et al., 2017). The focus of a Smart Energy System is to integrate renewable power sources and identify synergies between sub-sectors within the energy system. These synergies should define a pathway to a fluctuating renewable system where the energy infrastructure design is based on the general energy supply-demand. In a smart energy system, every technology within the system should have a designated purpose to define the overall energy infrastructure. (Lund et al., 2017).

A smart energy system is built to secure flexibility by combining the electricity, heating and transport sectors. These sectors can compensate for the lack of renewable resources when there is not enough wind power for the demand. (Lund et al., 2014). Through three grid infrastructures, the smart energy system is defined. The three infrastructures are Smart electricity grids, Smart thermal grids, and Smart gas grids. The Smart electricity grids connect the transport and heat sector with electric vehicles and heat pumps. The Smart thermal grids combine the heat and electricity sectors using the excess heat from energy production in the heat sector and enable heat storage. Smart gas grids combine sectors by utilising gas storage and gas refining to liquid fuels used in both the transport and heat sectors (Lund et al., 2014). Based on the three infrastructure, the smart energy system is defined as "*an approach in which smart electricity, thermal and gas grids are combined with storage technologies and coordinated to identify synergies between them to achieve an optimal* *solution for each individual sector as well as for the overall energy system"* (Lund et al., 2017).

As mentioned, every part of the system needs to retain a purpose to maintain flexibility and secure the parts are working together under different loads. The supply and demand are under 24 hours, not constant. Due to weather changes, renewable power production cannot be consistent because of sunny hours or the wind blows. Furthermore, the peak load of the system changes at certain hours of the day. The design needs to be flexible to ensure that renewable power is available when the demand is lower and in peak hours. To plan and create a smart energy system, it is necessary to analyze the existing system and develop a strategy to implement more renewables. There are five sections in an energy system: resources, conversion, relocation, exchange and storage, and demand (Lund et al., 2014).

Within those sections, different technologies are implemented with functions that comprehend the system in general. For future power generation, wind, water, and solar energy resources must be used thoroughly to ensure the fluctuation in the smart energy system. To simulate the future energy system, it is necessary to know each feature of the technologies and how to prioritize. Furthermore, the inputs and functions regarding the simulation have to be specified to analyze the whole system.

A smart energy system with fluctuating power sources is essential when 2 to 6 GW hydrogen production goals must be reached. As mentioned, the utilization of electrolysis must operate with power produced by renewables. Furthermore, the produced hydrogen needs to have a purpose within the system to be feasible. For simulation of electrolysis in an energy system, the produced hydrogen can have more purposes.

In this paper, the electrofuels are primarily used for the demand for hydrogen in transport and electrofuel production. Furthermore, the prioritisation of electrofuels produced needs to be addressed.

5.2 Technology readiness level (TRL)

Technology readiness level (TRL) is a measurement system for new technologies that allow an investor to define how mature the given technology is (Mankins, 1995). It provides the ability to the investors to compare certain technologies and works in the process of decision making. TRL has been used for NASA’s space technology programs for many years and later incorporated in the general technology management and development to define the current state of the technology and when it will be commercially available (Mankins, 1995). TRL is based on nine-step with the first step is the basic principles of the technology are observed and reported, to the last step where the technology is tested and mature and thoroughly tested to be incorporated as a part of a system, in NASA’s words, it is “flight-proven” (Mankins, 1995). In the table below is every step of the TRL model shown.

Step	Description
TRL 1	*Basic principles observed and reported.* - Scientific research begins, and the basic principles are applied into the research and development
TRL 2	*Technology concept and/or application formulated.* - Speculative level with identification of certain characteristics of the technology, no proof of concept.
TRL 3	*Analytical and experimental critical function and/or characteristic proof-of-concept*. - Active research and development and validation that the concept of the technology works.
TRL 4	*Component and/or breadboard validation in a laboratory environment*. - Concept-enabling validation by addressing requirements of system

	application. Testing the key elements of the technology.
TRL 5	*Component and/or breadboard validation in a relevant environment.* - Testing in a working environment, the technology is taken out of the laboratory, other technologies might be included in the demonstration to define efficiencies.
TRL 6	*System/subsystem model or prototype demonstration in a relevant environment.* - Prototypes will be tested in a relevant environment to present the demonstration of the technologies and grow confidence in the processes.
TRL7	*System prototype demonstration in a space environment.* - At the level of near maturity, the demonstration is still a prototype, but it is tested in the actual environment with a larger impact on the outcome.
TRL 8	*Actual system completed and “flight qualified” through test and demonstration.* - In Nasa terminology, it is the level of “true system development” where the technology reaches a qualification to be used in a program.
TRL 9	*Actual system “flight-proven” through successful mission operations.* - The technology is proven and works as intended in the system. Complications found in earlier steps are solved.

Table 19: Descriptions of the different steps of TRL Source: Mankins, John (1995)

The technology readiness level is used in the following sections to describe the technologies mentioned for hydrogen and e-fuel production from a system perspective. The maturity of a certain technology can be used in the decision making of a planning process and future development of a system.

5.3 Types of hydrogen

Production of hydrogen has different names related to what method is used for production. Some hydrogen is produced from natural gas, and another hydrogen production method uses nuclear power for production. The following section uses different types of hydrogen production methods mentioned with the other colour stamps used to describe the hydrogen output internationally.

5.3.1 Grey Hydrogen

Hydrogen produced with steam reforming from methane sources such as biogas or natural gas without carbon capture is called grey hydrogen. Grey hydrogen is not CO2 neutral and therefore suitable in an early phase, but more sustainable choices are preferred in the future. The level of CO2 emissions of this kind of hydrogen production is high, and this could be solved by capturing the carbon, which is done while producing blue hydrogen (Rossana et al., 2020)

5.3.2 Blue hydrogen

Blue hydrogen is produced from natural gas, which is methanol. The hydrogen atoms are extracted from the natural gas with pyrolysis, and the byproduct of CO2 is captured. Blue hydrogen is not considered carbon-neutral because of the use of natural gas (Bard et al., 2020). With blue hydrogen, 85 to 95% of the CO2 is captured and injected underground, so it does not get emitted, but through leakage in the pipeline, transportation lines may occur. Only 5 to 15% of CO2 is emitted in the atmosphere. Blue hydrogen is seen as an early state development product to use in the phase of changing to more CO2 neutral alternatives (Bard et al., 2020).

5.3.3 Pink hydrogen

Hydrogen produced with electricity from nuclear power is described as pink hydrogen. The production method is the same as green hydrogen with electrolysis, but the power stems from nuclear power plants which make it more limited considered to the other production methods because of the lower number of newer nuclear power plants (Bard et al., 2020). This method is CO2 neutral but is not seen as sustainable because of the toxic waste generated from the power plants (Bard et al., 2020)

5.3.4 Green hydrogen

Renewable hydrogen only produced by green electricity from wind power is described as green hydrogen. This production method has the highest efficiency and is total carbon neutral. Therefore, green hydrogen this seen as a significant potential for decreasing future carbon emissions (Bard et al., 2020). Green hydrogen is produced with electrolysis using alkaline, PEM or SOEC to create a pure hydrogen product with only O2 as the product (Pinsky et al. 2020). Green hydrogen is used in this report to utilize more carbon neutrality in the future in Denmark.

5.4 Connection models

Concerning the profitability of PtX, the connection model influences the applicable tariffs and tax costs. The industry that built electrolyzer plants has, as mentioned, an economic incentive, and the location of the plant must be beneficial regarding ownership of both electricity production and hydrogen production. The site and ownership impact how green the final product is perceived to be (Energinet, 2019). EU has made a renewable energy directive (RED) which specifies the ‘green value’ of the final product of the connected PtX facility. The ‘green value’ is estimated by the RE share of the PtX production and is corresponded to the average RE share of the electricity supply in two years (Energinet, 2019). The choice of connection models will impact the ‘green value’ of the final PtX products. The basic principles regarding the RE share on 100 pct are that it has to follow one out of three conditions. The three conditions are:

1. Direct connection to a RE facility with no connection to the public electricity grid and the RE facility should operate simultaneously as the PtX plant. This condition corresponds directly to the *off-grid model*.

2. Direct connection to a RE facility with connection to the public electricity grid, but it has to be documented that the used electricity stems from renewables and not supplied by the public grid in the period of PtX production. This condition is related to the *upstream model* or the *onsite model* during periods with no electricity import from the public grid.

3. Electricity imported from the public grid must be produced from renewable sources, and RE properties, including all other criteria, are demonstrated, such as electricity only applied once. The amount of documentation needed for this condition is still not precise, but it directly corresponds to the *off-side model*.

(Energinet, 2019)

Energinet (2019) has analyzed connection models to discuss and describe the factors that need to be considered when choosing an electrolysis plant's location and grid connection. In the following section will the onsite connection model and the offsite/upstream connection model be described.

5.4.1 Offsite model

The offsite connection model is when all electricity consumption of the plant is delivered from the public grid. The electrolysis and methane/methanol plant are located where the best possible facilities are CO2-source, storage capacity or a possible demand for the bi-products from the electrolysis process. For PtX production, this connection model seems to be the most flexible and has the most potential for upscaling (Energinet, 2019). Because the electricity consumption stems from the public grid, the final product from the processes is difficult to define as renewable. The general grid electricity is not always from renewable energy sources, and therefore, the tariffs and tax structure underlying the European Union makes it more expensive. It is hard to document the exact energy sources, and regulation complicates this model's profitability. (Energinet, 2019). In the illustration figure, 2 is the offsite connection model shown and how the facility uses the public electricity grid.

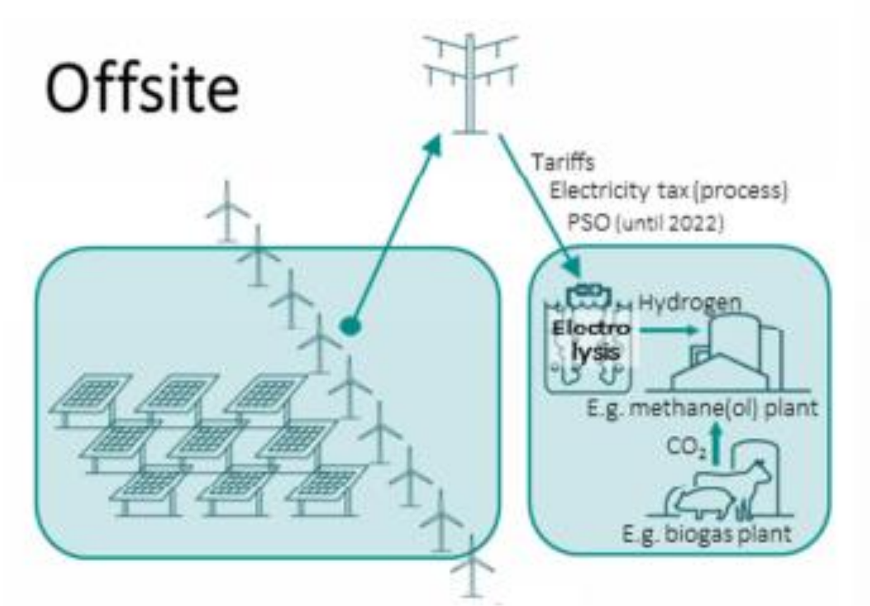

Figure 2: Illustration of the offsite connection model Source: Energinet (2019)

5.4.2 Onsite model

The onsite connection model is when the electricity production for the process happens onsite. To safe the tariffs, the electrolysis plant is connected to a renewable energy source and therefore, the energy used in the process is documented as renewable. It will be more feasible if the plant is located where the electricity demand is low, making it more difficult to find a place for both a plant and renewable energy sources close by. The factors of private investors place a role in this connection model because the energy sources and the plant should be owned by the same to gain profitability. Another utilization of the onsite connection model is the upstream model. The renewable energy is from the grid in this model, but the electrolysis plant is connected directly to the energy source. This will affect the plant that it will only have power at certain times due to demand from the publicity (Energinet, 2019). On figure 3 below is the onsite connection model illustrated

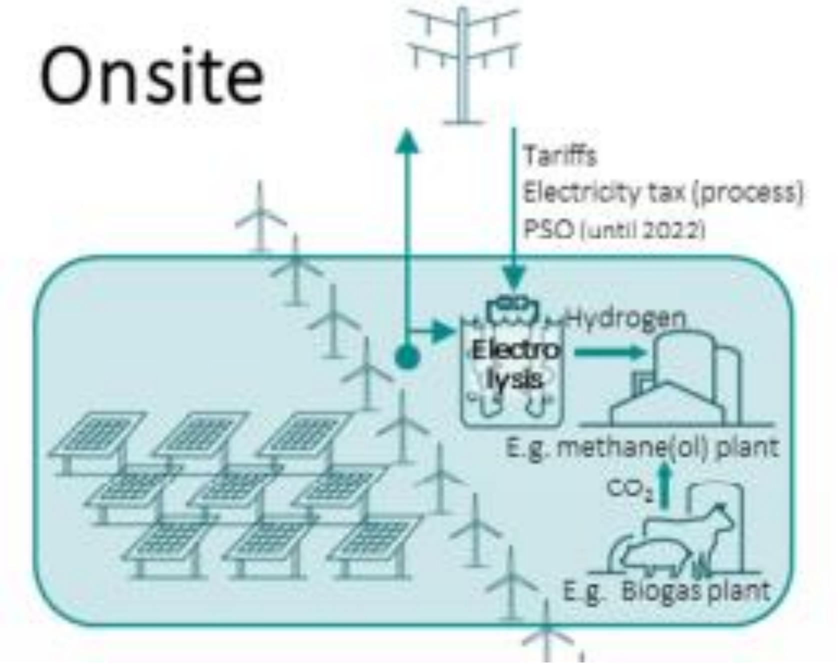

Figure 3: Illustration of the onsite connection model Source: Energinet (2019)

5.4.3 Upstream model

The upstream model is a variation of the onsite model. Wind and solar are connected directly to the electrolysis plant, and the electricity generation can be exported to the grid. Still, in the upstream model, the electricity is unlikely to be exported as it is in the onsite model. This model is most effective with a higher solar and wind capacity than the electrolysis capacity of the plant because the full potential of the product can be utilized. This plant's ‘green value’ seems higher than when energy is imported from the grid. The PtX production is supplied with 100 pct local and renewable electricity, and therefore, there are beneficial subsidies regarding this model (Energinet, 2019). The owner of an upstream connected facility can choose if it should be an onsite or upstream model, but the profitability producing higher green value makes the upstream model more feasible and outweigh the less efficient onsite model. Figure 4 below is the upstream connection model illustrated.

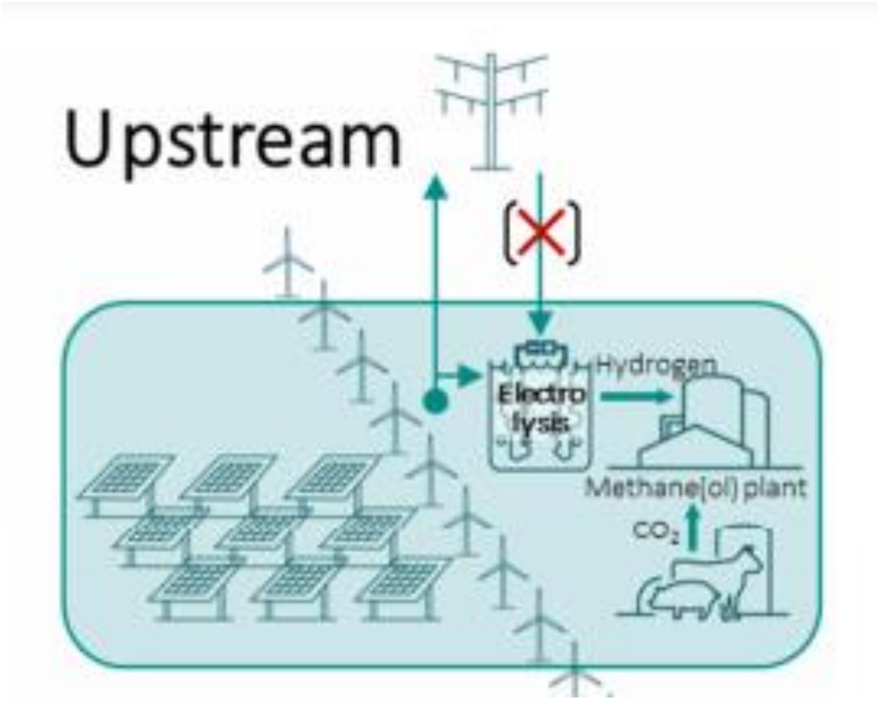

Figure 4: Illustration of the upstream connection model Source: Energinet (2019)

5.4.4 Off-grid model

The off-grid connection model is also a variation of the onsite model, but this model has no connection to the grid. The solar and wind power generated on the site can only be used for PtX production, making the off-grid model an inflexible choice for a connection model. The positive of this model is that the generated energy has to be used or stored in batteries, and therefore, the facility can run a lot of hours. This model is only relevant when the plant is located far away from the public power grid. Also, the ‘green value’ of this solution is not higher than the upstream model (Energinet, 2019). Figure 5 below is an illustration of the off-grid connection model.

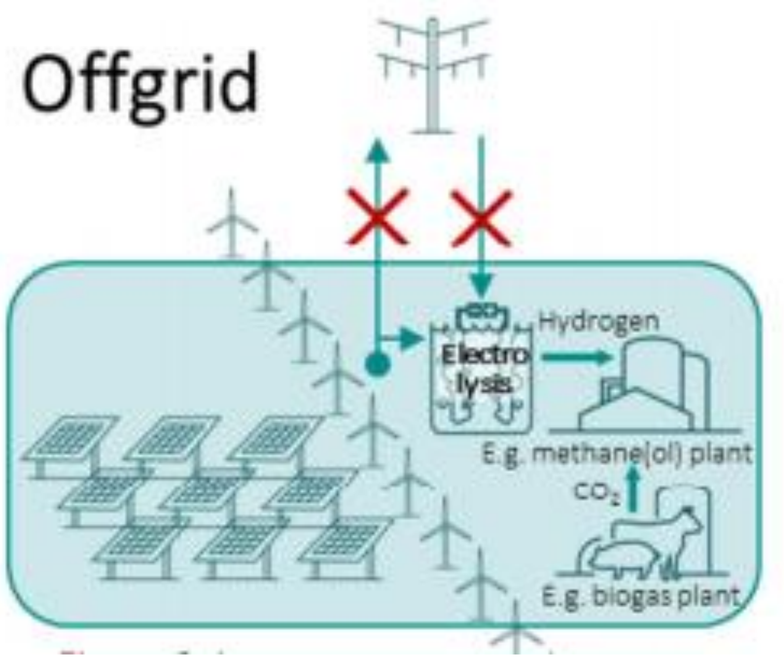

Figure 5: Illustration of the off-grid connection model Source: Energinet (2019)

6. Production pathways for proposed synthetic fuels

This chapter will analyze how the synthetic fuels of DME, Methanol, FT-SPK jet fuel, ammonia can be produced with a commercial TRL and further utilized as a transport fuel substituted with fossil fuels in the transport sector.

6.1 Hydrogen production

Electrolysis of water is built on the ground principles of extracting hydrogen from water using electrolysis (Danish energy agency, 2021). Electricity is used to create the chemical process of splitting hydrogen from water. A water molecule consists of two hydrogen atoms and one oxygen atom, and by setting electricity to the process, these atoms will split. The hydrogen ions (H+) and oxygen ions (O-) will go to each side of the electric current, with the H+ ions going towards the cathode electrode because of the negative charge. The positive ions and the OH- ions are going to the anode electrode. The reaction of water to hydrogen is:

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

6.1.1 AEC

AEC is the most common electrolyzer available, and a cell can work both atmospheric and under pressure up to 35 bars. It is on a practical level tested on up to 100 bars of pressure. Electrodes in an AEC electrolyzer are usually made of steel, nickel or nickel-plated steel. A micro-porous diaphragm separates the electrodes to avoid blending gasses. An AEC electrolyzer uses potassium hydroxide (KOH) as an aqueous solution which means that it is a water solvent solution. The water is added to the cathode where the OH- ions are going through the separator when it is under electric current. Hydrogen is then attracted from the cathode, and oxygen is produced from the anode (Danish energy agency, 2021).

The reaction of water to hydrogen in the cathode and anode:

Reaction in the cathode: $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Reaction at the anode: $2OH^- \rightarrow \frac{1}{2} O_2 + H_2O + 2e^-$

Parameter	**AEC**
Electrolyte	Potassium hydroxide (KOH)
Anode	Ni, Ni-Mo alloys
Cathode	Ni, NI-Co alloys
Maturity of technology	Mature (TRL 9)
Cold start-up time	120 minutes
Pressure	1 bar
Operating temperature	25°C
Input	Water and electricity
Hydrogen purity	>99,5
Efficiency	62-82%
Lifespan	> 100.000 hours

Table 20: Data from an AEC plant

(Danish Energy Agency, 2021; Schmidt et al., 2017; Pinsky et al., 2020)

6.2 CO2 Hydrogenation

This section will define how hydrogen and CO2 can be refined into renewable liquid fuels that ultimately can be substituted with fossil fuels in the part of the transport sector and the freight and shipping industry where decarbonization by electrification is a challenge. (Dieterich et al., 2020) Synthesis of H2 and CO2 to liquid fuels with electricity as feedstock can be performed by several techniques. This section will elaborate on the different techniques that can be applied to capture CO2, to synthesize H2 and CO2 into methanol which can be substituted with fossil gasoline, DME, or dimethyl ether which can be substituted with fossil diesel (Dieterich et al., 2020) and Fischer-Tropsch Hydro processed (FT-SPK) jet fuel which can be substituted with fossil Jet A and Jet A-1 fuel. (Mortensen et al., 2019)

6.2.1 Amine-based carbon capture

The amine-based absorption technique captures carbon from point sources by absorbing flue gasses in aqueous amine liquid solvents. Water-soluble salts are created as a by-product, and CO2 is recovered in a desorption column and a condenser, which are conceptualized as a stripper. (Dieterich et al., 2020) The amine-based solvent technique has a proven TRL on 9. (U.S. Department of energy, 2020). The amine-based carbon capture technology is the most mature demonstrated CO2 capture technology and has proven efficiencies of more than 90% extracted CO2 from its flue gas point source. (Danish energy agency and Energinet, 2020)

The process is driven by thermal energy and electricity. The thermal energy can either be obtained by installing a heat pump or extracted from a heat-producing point source like combined heat and power plants. Before the flue gas enters the process or the CO2 scrubber, the gas has to be pretreated in a pre-scrubber or a direct contact cooler. (Danish energy agency and Energinet, 2020)

The pretreatment process can be performed in two steps: cooling the flue gas and scrubbing acidic pollutants and fly ash. When the flue gas has been pre-processed, the gas will have a temperature of 30-40 degrees Celsius, and most of the pollutants present in the gas prior to the have been scrubbed out. The cooling of the flue gas involves removing heat, and the heat can be upgraded and used as a by-product in the district heating network. (Danish energy agency and Energinet, 2020) Suppose the amine-based carbon capture technology is installed in a facility that already involves the condensation of its flue gases. In that case, the pretreatment process is not needed since the gas will already be cooled, and pollutants have been scrubbed from the gas. Following the pretreatment of the flue gas, the gas is ready to be led to an absorption column where CO2 reacts with the amine liquid solvent. (Danish energy agency and Energinet, 2020)

The CO2 loaded amine solvent is then transferred to a desorption tower. The solvent then must be heated up to 130-150 degrees Celsius, and this can be achieved by installing a boiler at the bottom of the facility. In the case of a thermal powerplant, the heat can be extracted and upgraded from the plant's production. The heated CO2 and an aqueous solvent vapours from the top of the desorber, where it must be cooled in a condenser afterwards. (Danish energy agency and Energinet, 2020) The desorber operating conditions range from 100 degrees Celsius in the top of the desorber and 120 degrees Celsius in the bottom. The gas leaving the condenser will be a concentrated CO2 stream with a 30-40 degrees Celsius temperature. (Danish energy agency and Energinet, 2020)

The CO2 recovered from amine carbon capture instalments is highly pure and can obtain 99.95% or even higher purities. The main residue from the process is oxygen, nitrogen. If the CO2 needs to be stored or transported, it must be compressed before utilization. (Danish energy agency and Energinet, 2020) As mentioned, there is the potential of utilizing the excess heat that stems from the process. The amount of heat needed in the process is equal to the same amount of heat that must be removed or cooled. Since the process requires removing the heat, it can just as well be used in a district heating grid. The heat temperature levels typically will be available at 80 and 50 degrees, which is applicable to the temperatures in district heating grids. (Danish energy agency and Energinet, 2020)

6.2.2 Methanol synthesis

Methanol can be applied as a blend in gasoline and diesel with a methanol percentage of 85% (M85). Substitution gasoline with pure methanol (M100) has successfully been proven with petrol combustion engines in Sweden and Brazil. (Dieterich et al., 2020) The direct synthesis of methanol from CO2 and H2 described below has a TRL of 8 and has been proven and qualified in an operational environment and is commercially available. (Detz, 2019)

Methanol CH_3OH. The most prominent methanol synthesis process is the direct methanol synthesis according to the reaction chain below. The process occurs in the typical reactors, e.g., SRC (steam raising converter) reactor or an Adiabatic fixed bed reactor. (Dieterich et al., 2020) The process undergoes temperatures at 200-250 degrees celsius and with a pressure between 50-100 bar. The typical catalyst used in the reaction chamber is a copper oxide or cupric oxide and zinc oxide based on a carrier in aluminium oxide with a variable of stabilizing additives and promoters. E.g., Zirconium, chromium, and magnesium. (Dieterich et al., 2020) The output efficiency of the process and methanol yield range from 52-61%. As shown in the reaction chain below H_2O will be the remaining by-product of the methanol synthesis along with waste heat from the synthesis reaction. (Dieterich et al., 2020)

Reaction chain for CH_3OH with CO_2 and H_2 based feedstock,
$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \rightarrow \Delta H = -49.4\, kJ\, mol^{-1}$

The crude methanol cannot be utilized as fuel before an upgrade of the product has taken place. Impurities must be removed so that the methanol reaches the required fuel grade purity specifications. The impurities are removed in a single column distillation process where crude methanol is withdrawn from the synthesis and flashed at low pressures of 5-10 bar, which drives out the dissolved gases, which ultimately increases the purity. (Dieterich et al., 2020) The table beneath 21 is an extraction of technical data for gasoline and methanol, and this allows some comparison of the substituted fuels. Notable is the possibility of blending in and completely substituted with gasoline, further the higher octane and cetane number, and most importantly, the reduced pollution to the environment when combusted in engines. Newer studies show that methanol produced from renewable electricity with CO2 and H2 as feedstock can reduce greenhouse gas emissions by 86% compared to gasoline. (Dieterich et al., 2020)

Fuel type	Gasoline	Methanol
Liquid or Gaseous state	Liquid	Liquid
Chemical composition	$C_5 - C_{12}$	CH_3OH
Miscibility	-	Gasoline and diesel

Degradable	No	Yes
Pollution	High amounts of CO_2, SO_x and NO_x	None nitrogen oxide (NOx), and (SOx) *emissions* and very low particulate matter (PM) and carbon dioxide (CO2) *emissions.*
Density ($g\ 1^{-1}$)	715-780	791
Octane number	90-95	110-112
Cetane number	-	5

Table 21: Comparison of gasoline and methanol, Source: Vincent Dieterich et al. (2020)

6.2.3 DME synthesis

Dimethyl ether or DME can both be applied as a blend in diesel and completely substituted with diesel, though modification of the vehicles gas tank is needed to keep the DME in a liquid state. (Dieterich et al., 2020) The dehydration of methanol to dimethyl ether described below has a TRL of 8 and has been proven and qualified in an operational environment, and is commercially available. (Skov, I. R., & Mathiesen, B. V. (2017) DME or dimethyl ether CH_3OCH_3 can be obtained by further processing and dehydrating methanol in an adiabatic or cooled fixed bed reactor. The synthesis is conceptualized as the dehydration reaction between two methanol molecules. This process of producing DME is called the two-step or indirect process of producing methanol, followed by dehydration. The synthesis occurs at temperatures that range from 250-400 degrees Celsius and a pressure of 10-25 bar. (Dieterich et al., 2020) The typical catalyst used in the process is a solid acid catalyst, predominantly alumina, alumina-silica, and zeolites. The output efficiency of the process and DME yield range from 70-85 %. The remaining byproducts are water and waste heat from the synthesis. The following reaction chain is the actual synthesis of methanol to DME. The following reaction chains are the two-step approach to DME CH_3OCH_3 synthesis. (Dieterich et al, 2020)

Reaction chain 1, CH_3OH with CO_2 and H_2 based feedstock,
$CO_2 + 3H_2 \rightarrow CH_3OH + H_2O \rightarrow \Delta H = -49.4\, kJ\, mol^{-1}$

Reaction chain 2, dehydration of methanol
$2CH_3OH \rightarrow CH_3OCH_3 + H_2O \rightarrow \Delta H = -23.4\, kJ\, mol^{-1}$

For DME to utilized as a fuel, the crude DME must be distilled in a two-column distillation to obtain higher purities. The light ends are extracted from the liquid DME, and unconverted methanol and water are discharged from the distillation column and transferred to the methanol column, where the purified methanol is recycled in the DME reactor. The recycling of methanol and water allows purities of 99% and even up to 99.9% to be obtained. (Dieterich et al., 2020) Table 21 beneath is an extraction of technical data for diesel and DME, and this allows some comparison of the substituted fuels. Notable is that DME has a higher cetane number, low particle emissions and can be applied to blend in and completely substitute. Newer studies show that the dehydration of methanol to DME produced with renewable electricity, CO2 and H2 as feedstock compared to conventional diesel can obtain reductions of greenhouse gases of 82% per cent when combusted in engines. (Dieterich et al., 2020)

Fuel type	Diesel	DME
Liquid or Gaseous state	Liquid	Gaseous (liquid under the pressure of 5 bar)
Chemical composition	$C_{10} - C_{23}$	CH_3OCH_3
Miscibility	-	Diesel
Degradable	No	Yes
Pollution	High amounts of CO_2, SO_x and NO_x	No C-C binding and therefore almost none no particle emissions
Density ($g\ 1^{-1}$)	815-855	668

Octane number	-	-
Cetane number	45-53	55-60

Table 22: *Comparison of DME and diesel,* Source: Vincent Dieterich et al. (2020)

6.2.4 Fischer-Tropsch hydro processed Synthetic Paraffinic Kerosene or FT-SPK jet fuel.

Fossil aviation jet fuel is produced for use in gas turbine engines in aeroplanes. There are mainly two types of jet fuel Jet A and Jet A-1, which must be produced accordingly to international standards. Jet fuels consist of many different hydrocarbons. Since the exact chemical composition of jet fuel varies by its performance score, it is impossible to identify a fixed composition or ratio of hydrocarbons in jet fuel. (Mortensen et al., 2019) Kerosene-type jet fuel as Jet A and Jet A-1 has a ratio of 8 to 16 carbon atoms per hydrogen molecule and a freezing point of -47 degrees Celsius. Fossil jet fuels are produced with crude oil as input in a fractional distillation refinery, and when combusted in aeroplane turbines, jet fuel emits carbon dioxide and water vapour vaper. (Mortensen et al., 2019) Sustainable aviation fuels like FT-SPK have been certified for a 50% miscibility with fossil jet fuel, of the type of Jet A and Jet A-1. In theory, it is possible to produce FT-SPK jet fuel that is 100% similar to conventional jet fuel properties. (Mortensen et al., 2019) FT-SPK jet fuel can be produced with CO2 and H2 as feedstock. The process can be separated into two different approaches co-electrolysis and the reverse-water-gas-shift reaction. (Mortensen et al., 2019) To produce FT-SPK jet fuel, syngas CO and H2 must be processed by the Fischer-tropsch synthesis, and to feed the synthesis with syngas, the CO2 and H2 must be converted to syngas by the reverse-water-gas-shift (RWGS) reaction or by co-electrolysis. The most developed and only commercially available in the RWGS reaction chain, which takes place at temperatures of 350 to 600 degrees Celsius. The whole process has a TRL that range from 8-9. That range is caused by the different technologies present in the process. The second reaction chain is the main chemical reaction chain in Fischer-Tropsch synthesis, where syngas is converted to many hydrocarbons to produce alkanes further. (Mortensen et al., 2019)

Reverse-water-gas-shift reaction chain 1,

$$CO_2 + H_2 \rightarrow CO + H_2O$$

Fischer-Tropsch Reaction chain 2,

$$(2_n + 1)H_2 + n\,CO \rightarrow C_nH_{(2n+2)} + n\,H_2O$$

The output from synthesizing the syngas by the Fischer-Tropsch process is syncrude, and Fischer-Tropsch waxes, which further on can be hydrocracked or refined into FT-SPK jet fuel. The Fischer-Tropsch process can both occur at high and low temperatures, Low-Temperature Fischer-Tropsch (LTFT), which occurs at temperatures between 170-230 degrees Celsius and the High-Temperature Fischer-Tropsch (HTFT) which operates at temperatures that range from 250-340 degrees Celsius, both approaches operate at pressures of 20 to 25 bar and with cobalt as a catalyst. (Mortensen et al., 2019) The products range from alcohols, olefins, and paraffinic hydrocarbons, oxygenates, naphtha, diesel, and FT wax. Either proceeding can adjust the product distribution size with the low or high-temperature method. FT-SPK jet fuel is produced from the heavy end naphtha molecules and the light end diesel fuel, creating the chain of C6 to C16. (Mortensen et al., 2019)

The Fischer-Tropsch synthesis of the syngas itself and the refining of the syncrude into FT-SPK jet fuel can be put into four general steps. Step 1, hydrocracking or the adjustment of the hydrocarbon chain length to maximize the kerosene output. Step 2, the synthesis of the appropriate kerosene range aromatics. Step 3, the isomerization of linear hydrocarbons to lower the freezing point, and lastly, step 4, which involves the hydrogenation of the Syncrude to reduce olefins and oxygenate, the FT-SPK jet fuel yield of the whole process is approximately 70%. (Mortensen et al., 2019)

FT-SPK jet fuel compared to conventional jet fuel has several advantages. Still, the two primary advantages that stand out is the environmentally benefit from FT-SPK jet fuel produced from low carbon or renewable energy sources. (Danish energy agency and Energinet, 2021) In contrast to the high amounts of GHG emissions emitted under crude oil extraction and further in the refining of crude oil to jet fuel. In addition, newer research concludes that FT-SPK jet fuel also can reduce the formation of soot particles in contrast to crude oil-based jet fuel. The production of FT-SPK jet fuel does also provide other high-value industrial products compared to the production of conventional jet fuel. (Danish energy agency and Energinet, 2021)

“Depending on the process design, a lot of other products can arise or at least the building blocks for these products including gasoline, diesel, naphtha, ship fuel, waxes, lubricants, and a range of other petrochemicals which can be used in plastics, fertilizers, packaging, clothing, digital devices, medical equipment, detergents, tires, etc. Petrochemicals are also found in solar panels, wind turbine blades, batteries, thermal insulation for buildings, and electric vehicle parts” (Mortensen et al., 2019; 28)

The following table is an extraction of fuel properties. Notable is that FT-SPK jet fuel almost has the same properties as fossil Jet A-1 fuel but a higher cetane index and aromatics volume of the total fuel composition. The higher cetane index is an advantage, in contrast to the higher aromatics since the aromatics in the jet fuel are essential to prevent elastomeric seals from shrinking. This is why FT-SPK jet fuel currently only is applied as a blend in up to 50 %. (Danish energy agency and Energinet, 2021)

Properties	FT-SPK jet fuel	Jet A-1 fuel
Flash pt., in Celsius	54	48
Denisty kg/l	0.754	0.794
Aromatics volume in per cent	1	19.7
Freezing point in Celsius	-52	-49
Sulfur mass in percent	0.002	0.08
Cetane index	70	47

Table 23: Comparison of FT-SPK Jet fuel and Jet A-1 Fuel

Source: Danish energy agency and Energinet, (2021).

6.3 N2 Hydrogenation

Ammonia or NH_3 can be produced with hydrogen and nitrogen in the Haber-Bosch synthesis. This section will describe the applicability of ammonia as a fuel cell and how ammonia can be produced from renewable electricity, electrolysis-based hydrogen, and nitrogen captured from ambient air. The proposed process has a TRL on nine throughout the whole chain. As for utilization goes, MAN energy solutions have recently announced that they will have a commercial ammonia engine market-ready already in the year 2024. The two-stroke ammonia vessel engine is supposed to run on pure carbon and sulphur free ammonia, the combustion of the ammonia fuel, will, therefore, almost eliminate CO2 and SOx emissions from a well-to-wake perspective. (Lindstrand, 2020)

6.3.1 Ammonia synthesis and cryogenic distillation

The main process of producing ammonia can be split into four different stages, the first is the production and separation of nitrogen from ambient air, the second stage encompasses the compression of the syngas (H2 and N2), the third step the compressed syngas will be fed into the Haber-Bosch synthesis, and lastly, the fourth step involves cooling and separation of ammonia the remaining byproducts. The nitrogen can be obtained in an air separation unit, where Cryogenic distillation is the predominantly used technique to obtain the nitrogen, hence because of its high purities on 99.9% nitrogen (Rouwenhorst et al., 2019), but also because the technique locks the redundant argon gasses from the air in the oxygen by-product. Cryogenic distillation is the only technique utilized in large-scale industries because of the capacity range that complies with 100 MW and above. The Cryogenic distillation is commercial and has a TRL of 9. (Rouwenhorst et al., 2019). Before leading to the reaction chamber, the hydrogen and nitrogen must be compressed before being directed to the synthesis reactor. The most used compressor is the centrifugal compressor with ranging bars from 150-250. (Morgan, 2013) After the syngas is compressed, it can be transferred to the synthesis reactor, where the gas will react with industrial Fe (Iron-based) catalyst in temperatures of 350-550 and at pressures of 100-460 bars. The wide range of the conditions in the reaction chamber is because the Haber-Bocsh synthesis can be performed both under high and medium pressures. Both processes have a proven TRL on 9. The main difference between the two is the scale and electrical efficiency. (Rouwenhorst et al., 2019) The following reaction chain represents the synthesis of ammonia from hydrogen and nitrogen (Morgan, 2013),

Ammonia synthesis reaction chain,

$$N_2 + 3H_2 \rightarrow NH_3$$

The output is anhydrous ammonia with a purity rate of 99.5%. The remaining 0.5 consists of water and oil. Heat and purge gases consisting of oxygen and argon will also be a bi-product of the process. The electrical efficiency of the whole process is 66.4%, and the per pass conversion of syngas to ammonia range from 10-30%. To separate gaseous nitrogen and hydrogen leftovers from the ammonia, cooling of the gases is required. The cooling of the gases will liquefy the ammonia and separate it from the remaining gases. The remaining gases afterwards are captured and recycled back into the process. (Morgan, 2013)

6.4 Partial conclusion - Production supply chain pathways

The technologies define different pathways for synthetic fuel production with their currently TRL. In this study, the scenarios for the energy system in 2030 are elaborated, and therefore, TRL is important if the technologies must be implemented in the near future. On that account different pathway design to production of synthetic fuels is presented in the table below. Further, this chapter has defined how the synthetic fuels Methanol, DME, Fischer Tropsch-SPK jet fuel and Ammonia can be produced with CO2, N2 and H2. Common for all products is that they have a proven commercial TRL throughout the whole chain. The following list the different production supply chains for the proposed synthetic fuels.

Production supply chains	TRL
Alkaline hydrolysis → Amine based carbon capture → Methanol synthesis	8-9
Alkaline hydrolysis → Amine based carbon capture → DME synthesis	8-9
Alkaline hydrolysis → Amine based carbon capture → Fischer Tropsch-SPK jet fuel	8-9
Alkaline hydrolysis → Cryogenic nitrogen capture → Haber-Bosch synthesis	9

Table 24: Production pathways and average TRL for the whole supply chain

7. Critical factors concerning Danish PtX-development pathways

This chapter contains the reports second analysis and results. Adjustments to the reference model 2030 and modelling in EnergyPLAN can be viewed in appendix. The following chapter will identify the critical factors crucial to planning the proposed Danish PtX development pathways presented in the reports problem area.

7.1 Scenario 1, BF20

In Scenario 1, the initial start point was the projection of the renewable energy capacity in the Danish energy system in 2030. The projection is made by the Danish energy agency in their forecasting report BF20. Crucial for this scenario is the critical factors concerning Total CO2 emissions, Total cost, and the amount of potential of synthetic fuels that can be substituted with fossil fuels. The Danish 2030 70% CO2 reduction target and the reports problem area highlight that the energy system needs to reduce the total CO2 emission to 11,7 Mt or below to comply with the national target and the portion that the Danish energy system is responsible for reducing. The results or the critical factors from Scenario 1 shows that with the projected renewable energy capacity in 2030, the CO2 reduction target of 11,7 Mt or below can be obtained.

Furthermore, the scenario shows that 4.55 TWh of synthetic fuels can be substituted with fossil transport fuels. In addition, critical factors important for this development pathway is the amount of excess heat supplied to the system. The critical factors essential to the scenario or pathway are defined in the table below. A comparison between the DK2020 model, the reports Reference model 2030, and this scenario can be viewed in the report’s appendix. A comparison can also be drawn from section 4.3.3 in the report.

Scenario 1, BF20

Based on,

Input	Basisfremskrivning 2020 – Danmarks Klima- og Energifremskrivning (The Danish Energy Agency 2020b)	Photovoltaic, 6421 MW Wind, 6154 MW Offshore Wind 5630 MW

Table 25: Input in Scenario 1

Scenario 1, Critical Factors

Energy model	DK 2020 Model (Sorknæs, 2019)	Reference system 2030	**Scenario 1, 1476 MW**
Electrolysis capacity, MW	0	0	1476
Fossil fuels in transport, TWh/year	Jet Fuel 0,36. Diesel 30,77. Petrol 14,83.	Jet Fuel, 0,31 Diesel, 21,48 Petrol 9,5	Jet Fuel 0,21. Diesel 19,03. Petrol 7,5.
Synthetic fuels in transport, TWh/year	0	0	Jetfuel 0,1. DME, 2. Methanol 2. Ammonia 0,45.

CO2 Emissions (Mt)	29,76	12,31	11,09
Excess heat from electrolyser (TWh/year)	0	0	0,43
CEEP	0	3,16	3,16
COST (MEUR)	Total variable cost 7792, Fixed operation cost 3694, Annual investment cost 9606, Total Annual cost 21092	Total variable cost 3611, Fixed operation cost 3544, Annual investment cost 14430, Total Annual cost 21579	Total variable cost 3732, Fixed operation cost 3650, Annual investment cost 14696, Total Annual cost 22079
Renewable energy capacity	Photovoltaic, 952 MW Wind, 4232 MW Offshore Wind, 2051	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 5135 MW Wave 132 MW	Photovoltaic, 6421 MW Wind, 6154 MW Offshore Wind 5630 MW, Wave Power, 132 MW
Electrolysis electricity consumption in TWh	0	0	13,48

Fuel balance in TWh	Coal 19,85. Oil 66,57. N. Gas 25,65. Biomass 59,68 Renewable 21,20	Coal 0,95. Oil 35,89. N. Gas 11,46. Biomass 39,31 Renewable 49,00	Coal 0,95. Oil 31,34. N. Gas 11,86. Biomass 47,23. Renewable 57,31.

Table 26: Final results of Scenario 1

7.2 Scenario 2, 2000 MW Electrolysis capacity

In Scenario 2, the initial start point was the projection of 2000 MW Electrolysis capacity in 2030. The capacity is determined by the organization Klimapartnerskabet which works closely with the Danish parliament. Klimapartnerskabet and the danish parliament acknowledge the defined capacity of electrolysis in 2030 as a PtX development pathway that complies with the Danish 2030 70% CO2 reduction target. So, regarding the 11,7 Mt CO2 target, this scenario or system should not emit more than the 11,7 Mt of CO2 in total. With the pathway theory in mind presented earlier in the report, critical essential to obtaining this pathway is identified as, Total cost, Total CO2 emissions, amount of renewable energy needed to supply the system, and further the amount or potential of synthetic fuels substituted with fossil transport fuels. The critical factors crucial to this pathway is presented in the table below and shows that the CO2 target of 11,7 Mt has been obtained by more than 1 Mt. With an electrolysis capacity of 2000 MW, the system can produce 6.61 TWh of synthetic fuels, which in the system is substituted with fossil transport fuels. Further, the table shows the total cost of the system is equivalent to 22284 million EUROS.

Scenario 2, 2000 MW Electrolysis capacity,

Based on,

2-3 GW (to cover 70%)	Klimapartnerskabet	Regeringens klimapartnerskaber (2021)

Table 27: Input for Scenario 2.

Scenario 2, Critical Factors

Energy model	DK 2020 Model (Sorknæs, 2019)	Reference system 2030	**Scenario 2, 2000 MW**
Electrolysis capacity, MW	0	0	2000

Fossil fuels in transport, TWh/year	Jet Fuel 0,36. Diesel 30,77. Petrol 14,83.	Jet Fuel, 0,31 Diesel, 21,48 Petrol 9,5	Jet Fuel, 0,16 Diesel, 17,52 Petrol 7
Synthetic fuels in transport, TWh/year	0	0	DME 2,5 Methanol 2,5 Ammonia 1,46 Jetfuel 0,15
CO2 Emissions (Mt)	29,76	12,31	10,55
Excess heat from electrolyser (TWh/year)	0	0	0,58
CEEP	0	3,16	3,16
COST (MEUR)	Total variable cost 7792, Fixed operation cost 3694, Annual investment cost 9606, Total Annual cost 21092	Total variable cost 3611, Fixed operation cost 3544, Annual investment cost 14430, Total Annual cost 21579	Total variable cost 3738, Fixed operation cost 3715, Annual investment cost 14831, Total Annual cost 22284

Renewable energy capacity	Photovoltaic, 952 MW Wind, 4232 MW Offshore Wind, 2051	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 5135 MW Wave 132 MW	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 7685 MW Wave 132 MW
Electrolyser electricity consumption in TWh	0	0	18,23
Fuel balance in TWh	Coal 19,85. Oil 66,57. N. Gas 25,65. Biomass 59,68 Renewable 21,20	Coal 0,95. Oil 35,89. N. Gas 11,46. Biomass 39,31 Renewable 49,00	Coal 0,95. Oil 29.28. N. Gas 11,86. Biomass 49,31. Renewable 60,39.

Table 28: Final results of Scenario 2

7.3 Scenario 3, 2500 MW Electrolysis capacity

In Scenario 3, the initial start point was the projection of 2000 MW Electrolysis capacity in 2030. The capacity is determined by the organization Klimapartnerskabet as a PtX development pathway to reach the Danish 2030 70% CO2 reduction target. The critical factors crucial to this pathway is presented in the table below and shows that more than 1 Mt has obtained the CO2 target of 11,7 Mt. With an electrolysis capacity of 2500 MW, the system can produce 8.35 TWh of synthetic fuels, which in the system is substituted with fossil transport fuels. Further, the table shows the total cost of the system is equivalent to 22460 million EUROS.

Scenario 3, 2500 MW Electrolysis capacity,

Based on,

2-3 GW (to cover 70%)	Klimapartnerskabet	Regeringens klimapartnerskaber (2021)

Table 29: Input for Scenario 3.

Scenario 3, Critical Factors

Energy model	DK 2020 Model (Sorknæs, 2019)	Reference system 2030	**Scenario 3 2500 MW**
Electrolysis capacity, MW	0	0	2500
Fossil fuels in transport, TWh/year	Jet Fuel 0,36. Diesel 30,77. Petrol 14,83.	Jet Fuel, 0,31 Diesel, 21,48 Petrol 9,5	Jet Fuel, 0,16 Diesel, 16,38 Petrol 6,4

Synthetic fuels in transport, TWh/year	0	0	DME 3,1 Methanol 3,1 Ammonia 2 Jetfuel 0,15
CO2 Emissions (Mt)	29,76	12,31	10,08
Excess heat from electrolyser (TWh/year)	0	0	0,72
CEEP	0	3,16	3,16
COST (MEUR)	Total variable cost 7792, Fixed operation cost 3694, Annual investment cost 9606, Total Annual cost 21092	Total variable cost 3611, Fixed operation cost 3544, Annual investment cost 14430, Total Annual cost 21579	Total variable cost 3772, Fixed operation cost 3758, Annual investment cost 14930, Total Annual cost 22460
Renewable energy capacity	Photovoltaic, 952 MW Wind, 4232 MW Offshore Wind, 2051	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 5135 MW Wave 132 MW	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 8300 MW Wave 132 MW

Electrolyser electricity consumption in TWh	0	0	22,78
Fuel balance in TWh	Coal 19,85. Oil 66,57. N. Gas 25,65. Biomass 59,68 Renewable 21,20	Coal 0,95. Oil 35,89. N. Gas 11,46. Biomass 39,31 Renewable 49,00	Coal 0,95. Oil 27,54. N. Gas 11,86. Biomass 51,30. Renewable 63,14.

Table 30: Final results of Scenario 3

7.4 Scenario 4, 3000 MW Electrolysis capacity

In Scenario 4, the initial start point was the projection of 3000 MW Electrolysis capacity in 2030 and demand of 1.4 PJ synthetic aviation fuel and 8 PJ ammonia to substitute the total domestic demand of fossil transport fuels danish aviation and shipping. The capacity is determined by the organization Klimapartnerskabet as a PtX development pathway to reach the Danish 2030 70% CO2 reduction target. The critical factors crucial to this pathway is presented in the table below and shows that more than 1 Mt has obtained the CO2 target of 11,7 Mt. With an electrolysis capacity of 2500 MW, the system can produce 9,77 TWh of synthetic fuels, which in the system is substituted with fossil transport fuels. Further, the table shows the total cost of the system is equivalent to 22460 million EUROS.

Scenario 4, 3000 MW Electrolysis capacity – Domestic aviation and shipping

Based on,

2-3 GW (to cover 70%)	Klimapartnerskabet	Regeringens klimapartnerskaber (2021)
1,4 PJ, Domestic aviation 8 PJ, Domestic shipping	IDAs Klimasvar: Transport- og energiløsninger 2030	Aalborg Universitet and IDA (2020)

Table 31: Input for Scenario 4

Scenario 4, Critical Factors

Energy model	DK 2020 Model (Sorknæs, 2019)	Reference system 2030	**Scenario 4 3000 MW - Domestic aviation and shipping**
Electrolysis capacity, MW	0	0	3000

Fossil fuels in transport, TWh/year	Jet Fuel 0,36. Diesel 30,77. Petrol 14,83.	Jet Fuel, 0,31 Diesel, 21,48 Petrol 9,5	Diesel 15,65 Petrol 5,87
Synthetic fuels in transport, TWh/year	0	0	DME 3,63 Methanol 3,63 Ammonia 2,2 Jetfuel 0,31
CO2 Emissions (Mt)	29,76	12,31	9,7
Excess heat from electrolyser (TWh/year)	0	0	0,85
CEEP	0	3,16	3,16
COST (MEUR)	Total variable cost 7792, Fixed operation cost 3694, Annual investment cost 9606, Total Annual cost 21092	Total variable cost 3611, Fixed operation cost 3544, Annual investment cost 14430, Total Annual cost 21579	Total variable cost 3819, Fixed operation cost 3797, Annual investment cost 15019, Total Annual cost 22634

Renewable energy capacity	Photovoltaic, 952 MW Wind, 4232 MW Offshore Wind, 2051	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 5135 MW Wave, 132 MW	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 8895 MW Wave 132 MW
Electrolyser electricity consumption in TWh	0	0	26,83
Fuel balance in TWh	Coal 19,85. Oil 66,57. N. Gas 25,65. Biomass 59,68 Renewable 21,20	Coal 0,95. Oil 35,89. N. Gas 11,46. Biomass 39,31 Renewable 49,00	Coal 0,95. Oil 26,12. N. Gas 11,86. Biomass 52,94. Renewable 65,55

Table 32: Final results of Scenario 4

7.5 Partial conclusion - System perspective findings

A trajectory can be made throughout the four scenarios presented in this chapter. Common to all scenarios is the increasing total cost when introducing a higher electrolysis capacity, further reducing total CO2 emissions and the amount of synthetic fuels that can be produced and substituted. Furthermore, when increasing the electrolysis capacity, the share of renewable energy in the system can be increased, and the total annual cost will increase with the capacity. More troubling is the growing biomass consumption that follows with the expansion of the electrolysis capacity. This critical factor will be further examined in the reports third analysis. In these scenarios, the electrolysis runs all the time, and there is not much flexibility. This could influence biomass consumption. Therefore, the following analysis will try to lover the biomass consumption and introduce more flexibility in the system so that electrolysis will not run 100 pct of the year, which is both a critical factor and a theoretical down point of the findings in this chapter.

In contrast to the reports problem area and the Danish national 70 pct. CO2 reduction target in 2030, the comparison between the reference system 2030 and Scenarios shows that without electrolysis and synthetic fuels introduced in the system, it is impossible to reach the desired 11,7 Mt of CO2. But with electrolysis, all the scenarios or systems emit substantially lower amounts of CO2 from the system to the atmosphere. One could argue that there would be no need for further reductions when the crucial point of 11,7 Mt has been reached. Still, the value of 11,7 Mt depends upon those other sectors and industries that comply with the responsible portion of the total CO2 reduction to meet the national target. So, scenarios that emit below 11,7 Mt creates room for other industries and sectors not fully to comply with their target.

8. Introducing electrolysis flexibility in the energy system with hydrogen storage

In this chapter, hydrogen storage is introduced to identify what effect it has on the total annual costs, biomass consumption and runtime on the electrolysis. Therefore, the main aim of this analysis is to find the optimum of hydrogen storage with different electrolysis capacities in contrast to the performance parameters total annual cost and biomass consumption.

8.1 Optimum of hydrogen storage

This chapter contains the reports third analysis and results. Adjustments to the reference model 2030 and modelling in EnergyPLAN can be viewed in appendix. This analysis aims to find the optimum hydrogen storage in the systems and further the optimum hydrogen supply capacity. The optimum will be identified in contrast to the systems biomass consumption and total cost. So, the optimum will be defined at the lowest consumption and cost.

8.1.1 Scenario 5, 4000 MW – Electrolysis capacity

Scenario 5 is a further development or modelling of Scenario 2. The changes made to the system is the hydrogen storage capacity and the required hydrogen supply capacity. The table below shows the results from the actual analysis performed in the appendix of the report. The defined hydrogen storage optimum is 100 GWh. The defined optimum was identified by running multiple simulations with different GWh storage capacity. The biomass consumption and total cost for each system were extracted and defined in the following table.

GWh Storage	0	25	50	75	100	125	150	175	200	225	250
Biomass consumption	49,31	47,38	46,28	45,65	45,28	45,11	45	44,94	44,85	44,81	44,78
Optimum					X						
Total annual cost in MEURO	22284	22347	22313	22297	22295	22301	22311	22324	22336	22349	22363

Table 33: Scenario 5 optimum of hydrogen storage related to total annual costs

The following diagram is a graphical illustration of the results from Scenario 5 and the table above.

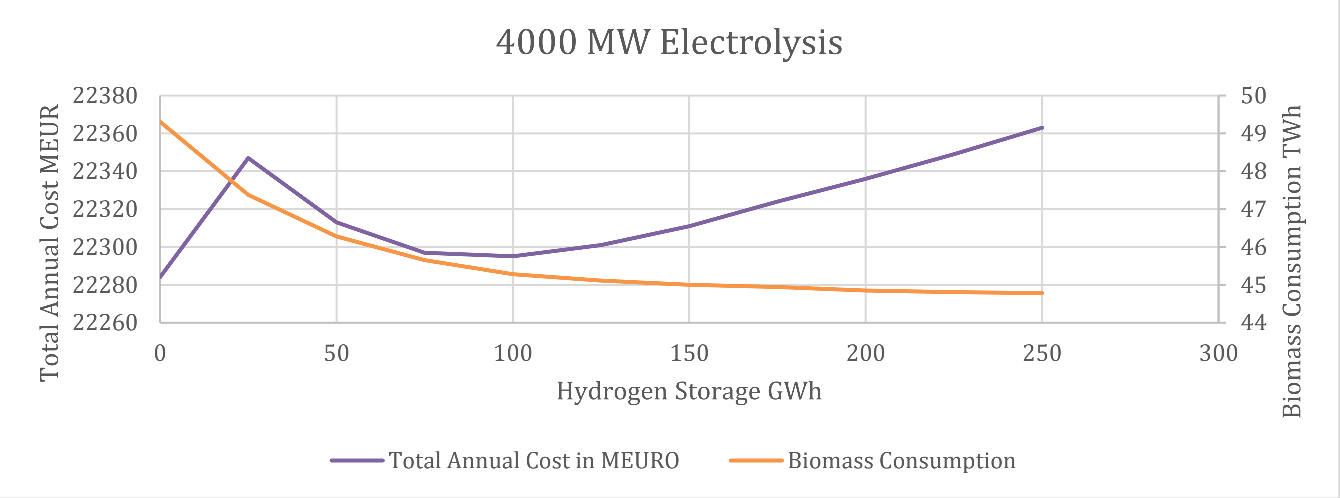

Figure 6: Diagram of data from Scenario 5

The following table lists the critical factors identified for scenario 5.

Scenario 5, Critical factors

Energy model	Reference system 2030	Scenario 2, 2000 MW	**Scenario (5), 4000 MW, 100 GWh Storage**
Electrolysis capacity, MW	0	2000	4000
Hydrogen Storage Capacity in GWh	0	0	100
Electrolysis run time	0	0	Average, 2075 MW

Fossil fuels in transport, TWh/year	Jet Fuel, 0,31 Diesel, 21,48 Petrol 9,5	Jet Fuel, 0,16 Diesel, 17,52 Petrol 7	Jet Fuel, 0,16 Diesel, 17,52 Petrol 7
Synthetic fuels in transport, TWh/year	0	DME 2,5 Methanol 2,5 Ammonia 1,46 Jetfuel 0,15	DME 2,5 Methanol 2,5 Ammonia 1,46 Jetfuel 0,15
CO2 Emissions (Mt)	12,31	10,55	10,35
Excess heat from electrolyser (TWh/year)	0	0,58	0,58
CEEP	3,16	3,16	3,16
COST (MEUR)	Total variable cost 3611, Fixed operation cost 3544, Annual investment cost 14430, Total Annual cost 21579	Total variable cost 3738, Fixed operation cost 3715, Annual investment cost 14831, Total Annual cost 22284	Total variable cost 3260, Fixed operation cost 3841, Annual investment cost 15123, Total Annual cost 22224

Renewable energy capacity	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 5135 MW Wave 132 MW	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 7685 MW Wave 132 MW	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 9235 MW Wave 132 MW
Electrolysis electricity consumption in TWh	0	18,23	18,23
Fuel balance in TWh	Coal 0,95. Oil 35,89. N. Gas 11,46. Biomass 39,31 Renewable 49,00	Coal 0,95. Oil 29.28. N. Gas 11,86. Biomass 49,31. Renewable 60,39.	Coal 0,95. Oil 29.28. N. Gas 10,88. Biomass 39,19. Renewable 67,32.

Table 34: Scenario 5 critical factors and final results

8.1.2 Scenario 6, 5000 MW – Electrolysis capacity

Scenario 6 is a further development or modelling of Scenario 3. The changes made to the system is the hydrogen storage capacity and the required hydrogen supply capacity. The table below shows the results from the actual analysis performed in the appendix of the report. The defined hydrogen storage optimum is 100 GWh. The defined optimum was identified by running multiple simulations with different GWh storage capacity. The biomass consumption and total cost for each system were extracted and defined in the following table.

GWh Storage	0	25	50	75	100	125	150	175	200	225	250
Biomass consumption	51,3	49,4	48,27	47,68	47,24	46,99	46,89	46,82	46,78	46,69	46,64
Optimum					X						
Total annual cost in MEURO	22460	22556	22518	22502	22497	22499	22507	22518	22531	22543	22556

Table 35: Scenario 6 optimum of hydrogen storage related to total annual costs

The following diagram is a graphical illustration of the results from Scenario 6 and the table above.

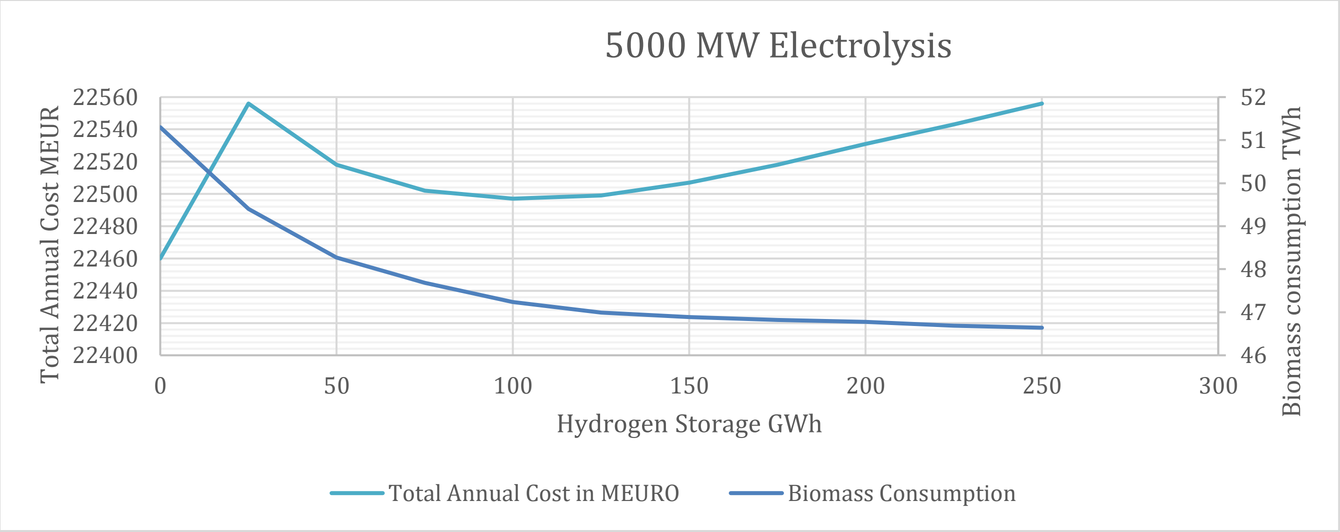

Figure 7: Diagram of data from Scenario 6

The following table lists the critical factors identified for scenario 6.

Scenario 6, Critical factors

Energy model	Reference system 2030	Scenario 2, 2500 MW	**Scenario (6), 5000 MW, 100 GWh Storage**
Electrolysis capacity, MW	0	2000	5000
Hydrogen Storage Capacity in GWh	0	0	100
Electrolysis run time	0	0	Average, 2593 MW
Fossil fuels in transport, TWh/year	Jet Fuel, 0,31 Diesel, 21,48 Petrol 9,5	Jet Fuel, 0,16 Diesel, 16,38 Petrol 6,4	Jet Fuel, 0,16 Diesel, 16,38 Petrol 6,4
Synthetic fuels in transport, TWh/year	0	DME 3,1 Methanol 3,1 Ammonia 2 Jetfuel 0,15	DME 3,1 Methanol 3,1 Ammonia 2 Jetfuel 0,15

CO2 Emissions (Mt)	12,31	10,08	9,87
Excess heat from electrolyser (TWh/year)	0	0,72	0,72
CEEP	3,16	3,16	3,16
COST (MEUR)	Total variable cost 3611, Fixed operation cost 3544, Annual investment cost 14430, Total Annual cost 21579	Total variable cost 3772, Fixed operation cost 3758, Annual investment cost 14930, Total Annual cost 22460	Total variable cost 3256, Fixed operation cost 3900, Annual investment cost 15254, Total Annual cost 22410
Renewable energy capacity	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 5135 MW Wave 132 MW	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 8300 MW Wave 132 MW	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 9965 MW Wave 132 MW
Electrolysis electricity consumption in TWh	0	22,78	22,78

Fuel balance in TWh	Coal 0,95. Oil 35,89. N. Gas 11,46. Biomass 39,31 Renewable 49,00	Coal 0,95. Oil 27,54. N. Gas 11,86. Biomass 51,30. Renewable 63,14.	Coal 0,95. Oil 27,54. N. Gas 10,80. Biomass 40,72. Renewable 70,58.

Table 36: Scenario 6 critical factors and final results

8.1.3 Scenario 7, 6000 MW – Electrolysis capacity

Scenario 7 is a further development or modelling of Scenario 4. The changes made to the system is the hydrogen storage capacity and the required hydrogen supply capacity. The table below shows the results from the actual analysis performed in the appendix of the report. The defined hydrogen storage optimum is 100 GWh. The defined optimum was identified by running multiple simulations with different GWh storage capacity. The biomass consumption and total cost for each system were extracted and defined in the following table.

GWh Storage	0	25	50	75	100	125	150	175	200	225	250
Biomass consumption	52,94	51,02	49,93	49,37	48,96	48,64	48,52	48,4	48,32	48,3	48,26
Optimum						X					
Total annual cost in MEURO	22634	22762	22722	22708	22700	22700	22707	22714	22725	22738	22751

Table 37: Scenario 7 optimum of hydrogen storage related to total annual costs

The following diagram is a graphical illustration of the results from Scenario 7 and the table above.

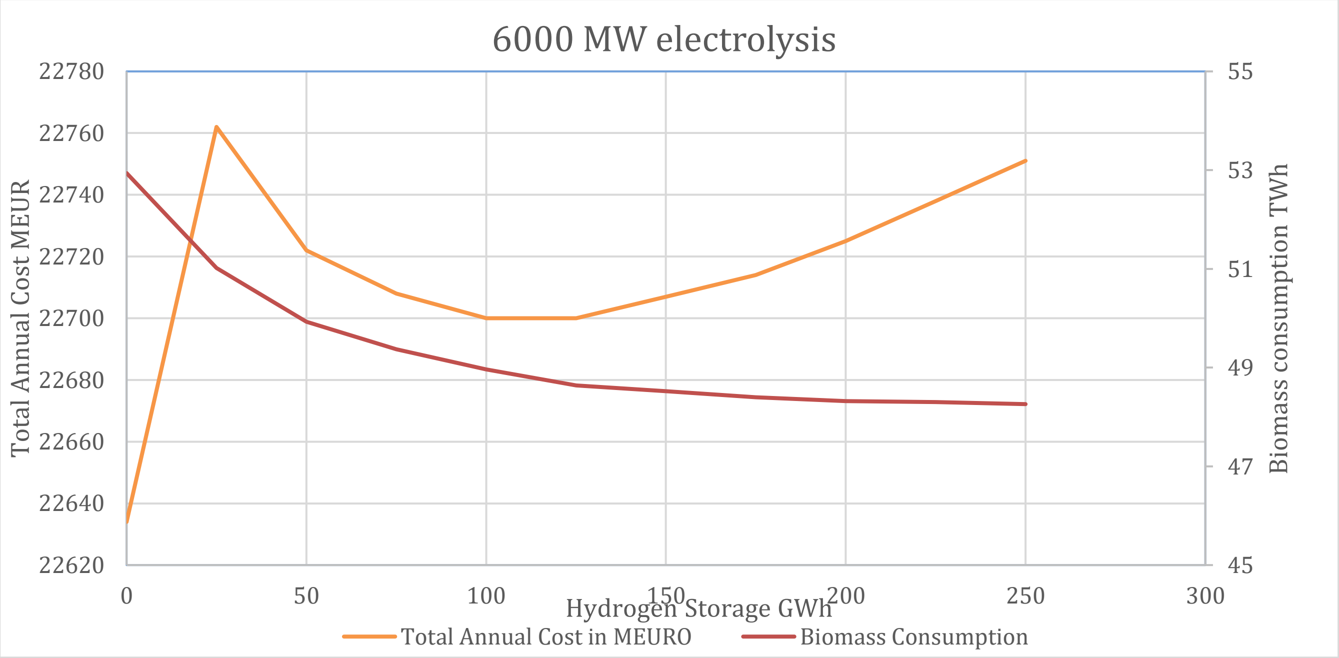

Figure 8: Diagram of data from Scenario 7

The following table lists the critical factors identified for scenario 7.

Scenario 7, Critical factors

Energy model	Reference system 2030	Scenario 2, 3000 MW - Domestic aviation and shipping	**Scenario (7), 6000 MW, 125 GWh Storage**
Electrolysis capacity, MW	0	3000 MW	6000
Hydrogen Storage Capacity in GWh	0	0	125
Electrolysis run time	0	0	Average, 3055 MW
Fossil fuels in transport, TWh/year	Jet Fuel, 0,31 Diesel, 21,48 Petrol 9,5	Diesel 15,65 Petrol 5,87	Diesel 15,65 Petrol 5,87
Synthetic fuels in transport, TWh/year	0	DME 3,63 Methanol 3,63 Ammonia 2,2 Jetfuel 0,31	DME 3,63 Methanol 3,63 Ammonia 2,2 Jetfuel 0,31

CO2 Emissions (Mt)	12,31	9,7	9,43
Excess heat from electrolyser (TWh/year)	0	0,85	0,85
CEEP	3,16	3,16	3,16
COST (MEUR)	Total variable cost 3611, Fixed operation cost 3544, Annual investment cost 14430, Total Annual cost 21579	Total variable cost 3819, Fixed operation cost 3797, Annual investment cost 15019, Total Annual cost 22634	Total variable cost 3193, Fixed operation cost 3968, Annual investment cost 15411, Total Annual cost 22572
Renewable energy capacity	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 5135 MW Wave 132 MW	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 8895 MW Wave 132 MW	Photovoltaic, 5000 MW Wind, 4800 MW Offshore Wind, 10840 MW Wave 132 MW
Electrolysis electricity consumption in TWh	0	26,83	26,83

Fuel balance in TWh	Coal 0,95. Oil 35,89. N. Gas 11,46. Biomass 39,31 Renewable 49,00	Coal 0,95. Oil 26,12. N. Gas 11,86. Biomass 52,94. Renewable 65,55	Coal 0,95. Oil 26,12. N. Gas 10,52. Biomass 40,65 Renewable 74,49

Table 38: Scenario critical factors and final results

8.2 Partial conclusion - System perspective findings

A trajectory can be made throughout the three scenarios presented in this chapter. Common to all scenarios is a reduction of the total annual costs, total CO2 emissions, biomass, and natural gas consumption of the system as an effect of the capability to introduce more renewable energy and flexibility in the system. The following table list the defined optimums of hydrogen storage for scenarios presented in the previous and current chapter.

Energy model	**Optimum of storage in GWh**	**Total annual cost in MEURO**	**Biomass consumption in TWh**	**Natural gas consumption in TWh**	**Total CO2 emission in Mt**
Scenario 2, 2000 MW	-	22284	49,31	11,86	10,55
Scenario 5, 4000 MW	100	22224	39,19	10,88	10,35

Table 39: Modelling from Scenario 2 to Scenario 5

Energy model	**Optimum of storage in GWh**	**Total annual cost in MEURO**	**Biomass consumption in TWh**	**Natural gas consumption in TWh**	**Total CO2 emission in Mt**
Scenario 3, 2500 MW	-	22460	51,30	11,86	10,08
Scenario 6, 5000 MW	100	22410	40,72	10,80	9,87

Table 40: Modelling from Scenario 3 to Scenario 6

Energy model	**Optimum of storage in GWh**	**Total annual cost in MEURO**	**Biomass consumption in TWh**	**Natural gas consumption in TWh**	**Total CO2 emission in Mt**
Scenario 4, 3000 MW	-	22634	52,94	11,86	9,7
Scenario 7, 6000 MW	125	22572	40,65	10,52	9,43

Table 41: Modelling from Scenario 4 to Scenario 7

9. Discussion

This chapter elaborate and discuss the different findings from the reports three analysis in contrast to the problem area.

Hydrogen production and synthetic fuels can decrease the CO2 emissions from the transport sector. Still, strategic planning is necessary to ensure the energy system can handle the amount of production capacity planned. Further, the electricity input in the production of hydrogen must stem from renewable sources before there is a ‘green value’ in the product. As mentioned in Scope (2), there are contradicting meanings regarding hydrogen production because companies producing hydrogen see hydrogen as a business case instead of a part of a system. With too much synthetic fuel and electrolysis capacity, biomass consumption will rise due to a lack of energy. This is shown in the chapter “*Critical factors concerning Danish PtX-development pathways*” (7), where biomass consumption rises. To reach the targets for 2030 in the span from 2 to 6 GW, it is necessary to implement the production in the near future to comply with the national target of 70 pct. Reduction of CO2 emissions in 2030. In this study, the available technologies are mentioned. The pathways of technologies are identified with the highest technology readiness level (TRL). There are many solutions with different weaknesses and strengths, but the TRL has been too low compared with the identified technologies used in the pathway design for synthetic fuel production. The efficiencies from the technologies with the highest TRL are used in the modelling of the 2030 scenarios. In that regard, it is possible to design and integrate commercial synthetic fuel production in the national energy system today.

The amount of offshore wind energy which must be implemented in the process is something that is not considered in this study. Still, it will influence the willingness to incorporate facilities for synthetic fuel production in the national energy system. In Denmark, there are 1699 MW offshore wind. Still, in the 6000 MW scenario with 125 GWh storage, there is a need for 10840 MW, so concerning the planning of the capacity of synthetic fuel production, it is necessary to plan the offshore wind capacity. Furthermore, the reports' third analysis showed that concerning the run time of the electrolysis, total biomass consumption in the system, and the system's total cost, it's crucial to plan the hydrogen supply capacity and storage capacity strategically.

The final production of synthetic fuels is limited under EU legislation and cannot be used to the fullest because of displacement regulation. Until 2030 the Danish parliament has agreed to prioritize fuels produced by renewable energy. The regulation of CO2 displacement where seven pct. of the total fuel distribution needs to be CO2 displaced fuels. The government expects a CO2 reduction of 1,4 Mt in 2030 from displaced fuels, which is not much compared to the energy sector must decrease emissions from 30 Mt to about 11,7 Mt (The Danish Parliament, 2020). The EU regulation impacts the targets because the fuel quality is high, and therefore, it is not possible to use more synthetic fuel in the sector. By not having the opportunity to phase out conventional fuels to the fullest, the potential of renewable fuels decreases. Therefore, the EU must change the regulation on synthetic fuels before 2030. Furthermore, the first analysis of the report defined that the proposed fuels today have a blend-in limit, which creates some barriers for Scenario 3 in the second analysis and Scenario 6 in the third analysis. The realization of the scenarios depends upon a complete substitution with fossil jet fuel and diesel to ammonia and FT-SPK jet fuel, and not only a blend-in substitution.

10. Conclusion

The report has proven how critical factors like fuel consumption, total cost, total CO2 emissions crucial to the Danish energy system and proposed PtX development pathways can be identified by modelling and simulating different pathways or energy systems. To model and simulate different the different proposed hydrogen capacity pathways presented in the problem area and method section, the reports first analysis aim was to define how the production of hydrogen and refining of H2, CO2, and N2 into the synthetic fuels DME, methanol, ammonia and FT-SPK jet fuel can be done in theory and practice. The analysis was designed with the metric that all technological components in the production supply chain should have a commercial TRL on 8. The result of the analysis was four proposed production pathways,

Alkaline hydrolysis → Amine based carbon capture → Methanol synthesis (TRL, 8-9).
Alkaline hydrolysis → Amine based carbon capture → DME synthesis (TRL, 8-9).
Alkaline hydrolysis → Amine based carbon capture → FT-SPK jet fuel (TRL, 8-9).
Alkaline hydrolysis → Cryogenic nitrogen capture → Haber-Bosch synthesis (TRL, 9).

The efficiencies and cost for each process were then added to the reference system 2030, which was modelled to simulate the different scenarios. The second analysis aimed to identify critical factors crucial in planning the proposed hydrogen capacities by Klimapartnerskabet. Critical factors are CO2 emissions, total cost, fuel consumption, renewable energy capacity, and the potential of synthetic fuels substituted with fossil fuels in the transport sector. The critical factors were identified partially to discover steps that can be taken and which steps must be avoided to comply with the Danish national 70% CO2 reduction target. In all proposed scenarios, the total CO2 emission reduction of the system from 30 Mt to 11,7 Mt is achieved. In some of the scenarios, the target is fulfilled with more than one 1 Mt. Further a trajectory throughout the four scenarios presented in the second analysis. The trajectory proves that when introducing a higher electrolysis capacity, the cost is increased. Further is the reduction of total CO2 emissions and the amount of synthetic fuels produced and substituted.

In addition, when increasing the electrolysis capacity, the share of renewable energy in the system can be increased. One critical factor or step which must be avoided or kept in mind when planning for PtX development pathways is the growing biomass consumption that follows with the expansion of the electrolysis capacity. This critical factor arises from the electrolysis that runs at full capacity every hour of the year, increasing the cost of the system and the fuel consumption to supply the electrolysis in each hour of the year when renewable electricity isn't available. None of the proposed hydrogen capacity pathways presented in the problem area and methodology section mentions any planning or strategic thinking of the crucial hydrogen storage capacity, which the third analysis in the report clearly showed is necessary to create flexibility in the run-time of the electrolysis and the systems production and consumption in total. When introducing the optimum hydrogen storage to the system, the system's total cost and biomass consumption reduce considerably.

The third analysis in the report calculated and defined the optimum of hydrogen storage and required electrolysis capacity to create flexibility in the system and reduce the system's total cost and fuel consumption. This was proven in the reports Scenario 5 (4000 MW, 100 GWh storage), Scenario 6 (5000 MW, 100 GWh storage), Scenario 7 (6000 MW, 125 GWh storage), which showed the total CO2 emission, total cost, total biomass, and coal consumption can be considerable reduced when introducing the optimum of hydrogen storage. The optimum was found and calculated by simulating multiple scenarios with the different storage capacities, then evaluated and compared in contrast to total cost and biomass consumption. The trajectory throughout the reports three analysis shows how critical factors concerning PtX development pathways in the Danish national energy system in 2030 can be identified by designing and simulating different energy model scenarios in EnergyPLAN concerning the fulfilment of the Danish national CO2 reduction target of 70% in 2030.

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