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FEASIBILITY STUDY FOR A WEST DANISH HYDROGEN TRANSMISSION GRID – PREREQUISITES AND PRELIMINARY ANALYSIS

1. Introduction

Green hydrogen is an essential element in the green transition, and the potentials for hydrogen production in Denmark are significant. Large-scale production of hydrogen/PtX requires a well-designed hydrogen infrastructure that can ensure cost-effective transport and storage of hydrogen while providing access to export markets.

To support this, the hydrogen infrastructure must be designed to support both the short-term and long-term transport and flexibility needs for the Danish producers and consumers of hydrogen. This includes designing the hydrogen system from the start based on the long-term goals for both offshore wind development, exports to i.e., Germany and a growing a market for production of e-fuels in Denmark. The interaction between the electricity and hydrogen systems ensures that Denmark can build renewable energy faster, to a greater extent and more cost-effectively.

In the on-going feasibility study, Energinet is in the process of clarifying the socio-economic value creation of establishing high-capacity hydrogen transmission coupled with large-scale hydrogen storage. A hydrogen infrastructure is expected to positively impact the producer surplus in the electricity market. Likewise, it is also expected to have a positive impact on both producer and consumer profits in the (upcoming) hydrogen market. Furthermore, there will be value in the hydrogen infrastructure being planned in conjunction with the future investments in the electricity transmission grid. In this way, the expansion needs for electricity infrastructure can be minimized and hydrogen production will provide an opportunity to contribute to balancing an energy system based on fluctuating renewable energy.

The feasibility study, which was launched in June, is off to a good start. Energinet now shares some preliminary results that may change as we go further with the study. We look forward to constructive dialogues that will contribute to the qualification of the results for the study.

Following topics are covered:

- Prerequisites and coherence with electricity infrastructure (Section 2)
- Considerations on pipeline routing (Section 3)
- Preliminary technical/economic analyses (Section 4)
- Cross-border activities (section 5)

2. Preconditions and the coupling with electricity system

Based on Energinet and the Danish Energy Agency's market dialogue from 2021 and the already announced PtX project plans, it is estimated that hydrogen infrastructure at transmission level before 2030 is most interesting in Jutland. There is also concrete interest in export of hydrogen to Germany as well as access to hydrogen storage.

The Danish Energy Agency, Evida and Energinet have jointly conducted a new market dialogue in 2022 with a good response from relevant stakeholders. The conclusions will be published in collaboration with Evida, the Danish Energy Agency and KPMG (who have assisted with the market dialogue) at the end of October 2022. The preliminary results indicate great interest in both domestic use of hydrogen for e-fuels as well as direct hydrogen exports.

Based on the above, Energinet's feasibility study therefore focuses on establishing a hydrogen transmission and storage infrastructure. The study does not include the need for adjacent distribution infrastructure nor potential hydrogen clusters. Transmission infrastructure in the rest of Denmark may soon prove relevant and may be analyzed subsequently. Several deliveries from this first feasibility study are expected to be used in similar future studies and regardless of where transmission infrastructure is located. This applies, for example, to the socio-economic method development, the market model, screening processes, methods for determine cost estimates and schedule.

The fact that the feasibility study focuses on hydrogen infrastructure in Jutland is also supported by the political agreements and ambitions includede in the PtX strategy from March 2022, the Esbjerg Declaration from May 2022 on the expansion of offshore wind in the North Sea area and the climate agreement from June 2022.

Overall, the Danish PtX strategy sets the ambition of 4-6 GW of electrolysis capacity by 2030, with emphasis on hydrogen being produced with green power. Consequently, there is an rapid need for solar and wind

Today, there are approx. 4 GW offshore and coastal wind turbines in Denmark. By 2030 there will be approx. 10 GW. The majority of this is expected to be in the North Sea and connected to the electricity grid on the west coast of Jutland.

There is also a significant expansion of onshore solar and wind power from approx. 7 GW today to approx. 30 GW in 2030. Potential Energy Island in both the North and Baltic Seas of up to 3 GW each in the years immediately after 2030 are also studied.

In the longer term, there are political ambitions to exploit the full wind potential in the Danish part of the North Sea, which is estimated at 35 GW and to expand with additional PtX plants both onshore and offshore.

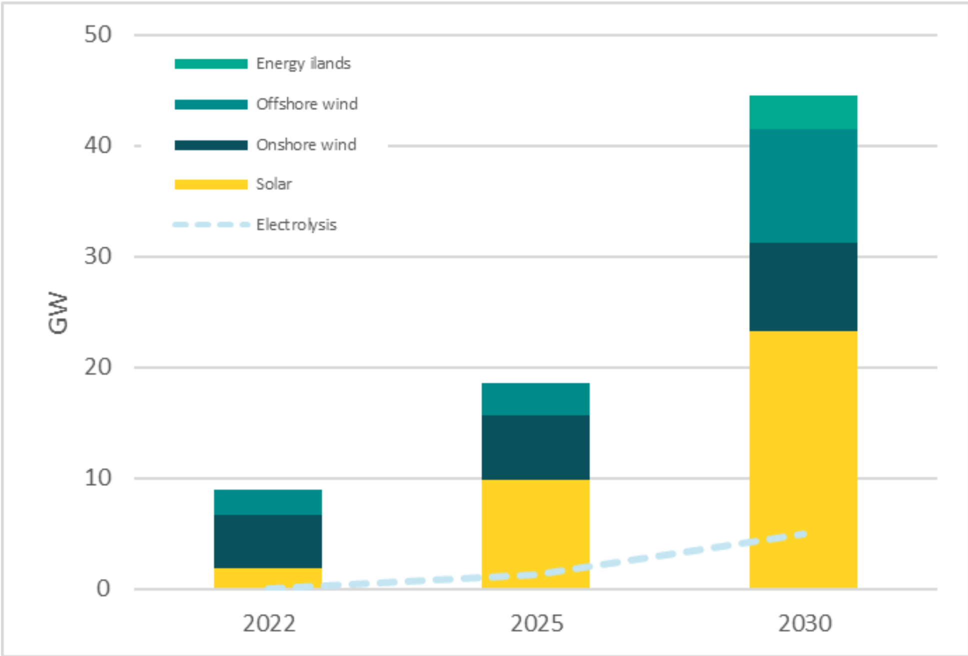
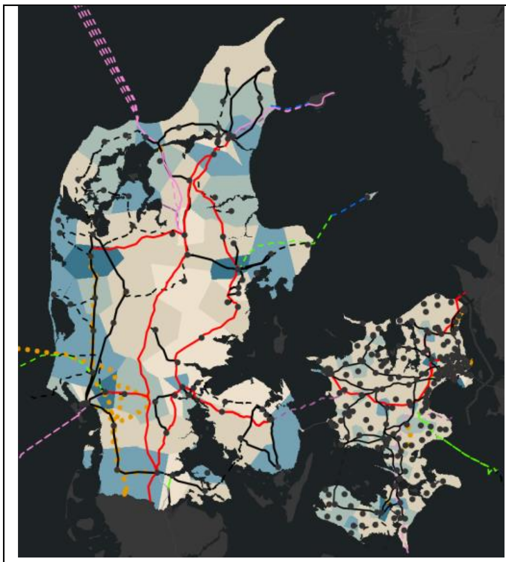


Figure 1. Development in electrolysis and electricity production capacity from renewable energy sources (including Energy Island Bornholm) until 2030. These figures are based on the danish political targets for renewable energy and PtX.

The exact locations of new PtX plants are still unknown. An important element in the final decision is, however, access to electricity supply. In the near future there will be a significant "surplus" of electricity in large areas of Jutland. Combining the connection of new offshore wind and the location of future PtX plants will be economically effective in reducing the need for new electricity transmission grid.

In the feasibility study the basis for the geographical location in 2030 are access to electricity, together with information from the Market Dialogue 2022 and the PtX agreement's ambitions for 4-6 GW of electrolysis capacity, Figure 2.



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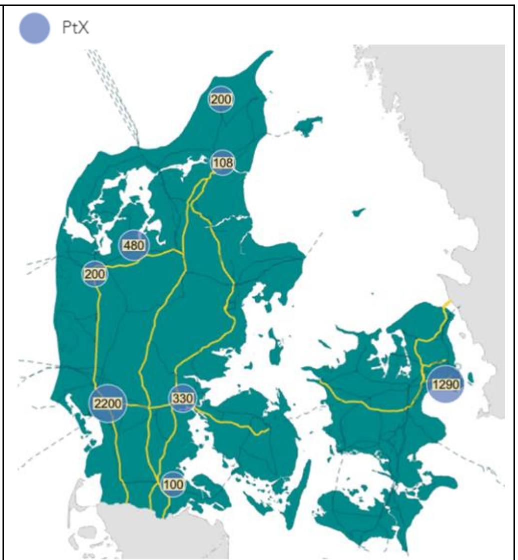

Geographical distribution of capacity 2030 [MWelectricity]

Figure 2 Areas with current local electricity surplus and assumed location of PtX plants in 2030. 5 GW of electrolysis has been included (from the PtX agreement 4-6 GW), of which

> *approx. 3.6 GW is expected to be in Jutland while approx. 1.3 GW is expected to be located on Zealand.*

When the results from the Market Dialogue 2022 are available, these will be included in the further analyses.

3. Considerations on pipeline routing

Figure 3 below outlines an potential start of the Danish hydrogen transmission network. With its proximity to the North Sea, Jutland is central to exploiting the large renewable energy potential in the short term in relation to offshore wind as well as onshore wind and solar - and in the long term from future energy islands, which may be able to land RES as both electricity and hydrogen. The considerations behind the routing are primarily based on the large nodes in the electricity transmission network, where the offshore wind and the large electrolysis plants are expected to be connected. From here, it will be possible to transport hydrogen for storage to Ll. Torup as well as connections to the adjacent systems, including exports to Germany.

For future analyses, Energinet has identified possible transmission connections from Ll. Torup hydrogen storage to Aalborg and/or Trige. In addition, a connection to a possible Swedish hydrogen network and infrastructure on Zealand and from Bornholm can be thought of, as shown in Figure 3. However, these connections are not included in this feasibility study, but will need to be analyzed further in future studies.

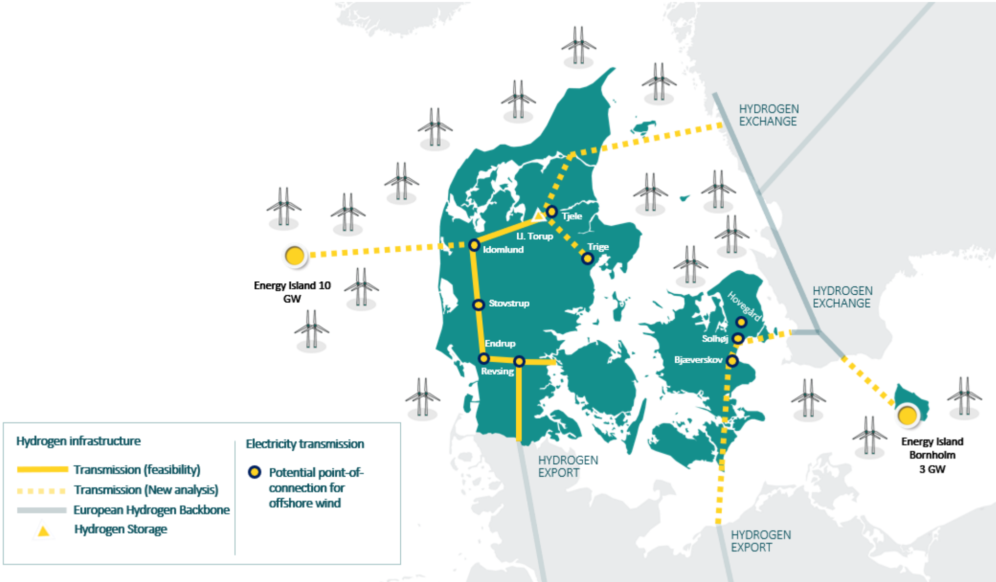

Figure 3. *Illustration of hydrogen transmission network covered by the feasibility study as well as possible transmission networks, which have been identified and will be analyzed in new studies.*

4. Preliminary technical/economic analyses

4.1 Preliminary capacity analyses

The feasibility study explores the socio-economic perspectives of a hydrogen transmission network that connects the PtX stakeholders announced areas of interest with hydrogen cavern storage in North Jutland and the German market, where there is a high demand for green hydrogen. Access to Germany is seen as crucial for an accelerated Danish expansion of renewable energy production, as contrary to Denmark, Germany already has significant demand for hydrogen. It is expected that by 2030 there will be a German import demand of 76-96 TWh[1] in total. Access to the German market is not an obstacle to establishing a strong Danish PtX industry – on the contrary, it can contribute to faster construction of the necessary infrastructure to support a national hydrogen and PtX-market. Other perspectives to be included, are the fact that there is a large district heating base in Central and South Jutland, which enables the usages of surplus heat from hydrogen production plants.

The feasibility study examines a west-east hydrogen infrastructure between Esbjerg and Fredericia together with a north-south connection from Ellund (the border with Germany) to hydrogen storage in Ll. Torup. As a starting point, the study explores the possibility of establishing 36" transmission pipelines with a design pressure of 80 bar to support the accelerated renewable energy expansion.

By designing the transmission grid for a pressure of 80 bar, the system will be future-proofed as the system capacity can be increased as needed to handle increasing hydrogen production from established and new projects, including future connections of the Danish energy islands. In the initial phase, the hydrogen pipeline can be operated at lower pressures, e.g., 35 bar, which can be the discharge pressure from the electrolysis. The transport capacity can then be increased in the long term by establishing one or more compressor stations. Energinet's preliminary analyses show that a pipeline diameter of 36" will be able to transport of large amounts of hydrogen. This minimizes the risk of having to construct new parallel hydrogen pipelines in the future. Figure 4 below shows preliminary calculations of the capacity potential of a grid operated at input pressures of 78 bar and 35 bar respectively.

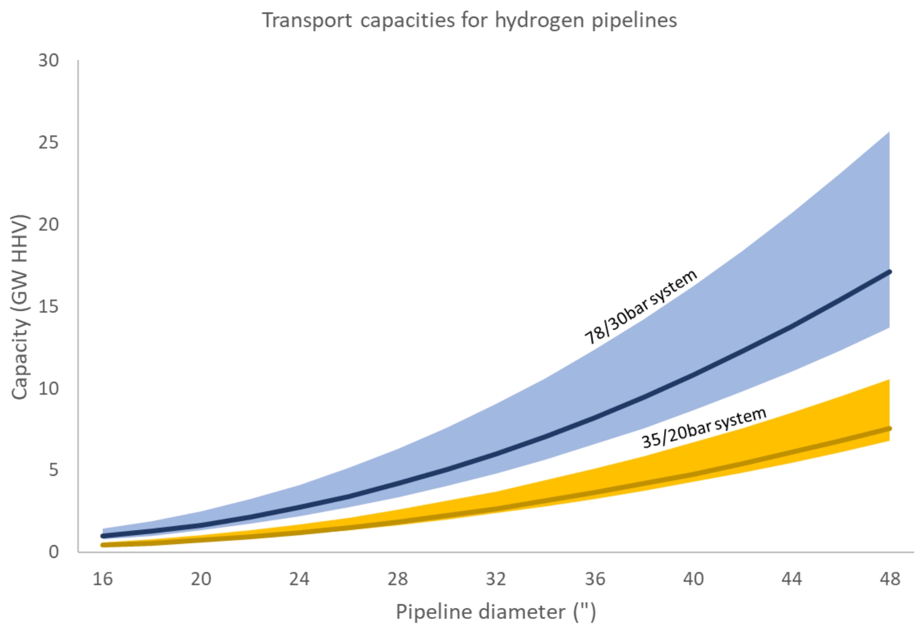

Figure 4. The transport capacity for different pipeline diameters with 78 bar inlet pressure and 30 bar discharge pressure (blue) respectively 35 bar inlet pressure and 20 bar discharge pressure (yellow). The capacity is calculated for the gross calorific value of hydrogen (HHV).

The analyses show that a pipeline dimension of e.g., 36" and 78 bar provides a capacity of 10 GW, which future-proofs hydrogen infrastructure on pipeline sections with expected large hydrogen production in the future. Coupled with the possible repurposing of the existing gas

[1] Den tyske regering: The National Hydrogen Strategy (link)

pipeline between Frøslev-Egtved II pipeline, which is 30" and with design pressure of 80 bar, it will ensure the capacity for significant exports. On the German stretch from Ellund to Hamburg, a previous study has shown that existing natural gas infrastructure can be repurposed to a large extent. Repurposing provides thereby opportunities to establish the hydrogen infrastructure both cheaper and potentially faster.[2]

Larger pipeline dimensions and high design pressure provide additional advantages in terms of being able to deliver flexibility on the hydrogen production side, enabling flexibility into the power system. Linepack, which is an expression of the amount of gas available in the pipeline system between a minimum and a maximum operating pressure, can be used in conjunction with underground storage of hydrogen. Figure 5 below shows linepack potentials for different pressures and pipe dimensions. In the initial phase where the grid is operated at approximately 35 bar, a 36" transmission pipeline will have a linepack storage of approximately 3 GWh/100 km. If the pressure is raised to approx. 78 bar, there will be a linepack storage of approx. 10 GWh/100 km, which corresponds to approx. 10% of a hydrogen cavern storage. Large-scale cavern storage, which also supports rapid variations between injection and extraction in interaction with the hydrogen transmission system, is expected to quickly become relevant to optimize value chains, where linepack volume (i.e., pipeline dimension and maximum differential pressure) plays a significant role in the overall system design. The need for linepack volume will be included in the continued analyses.

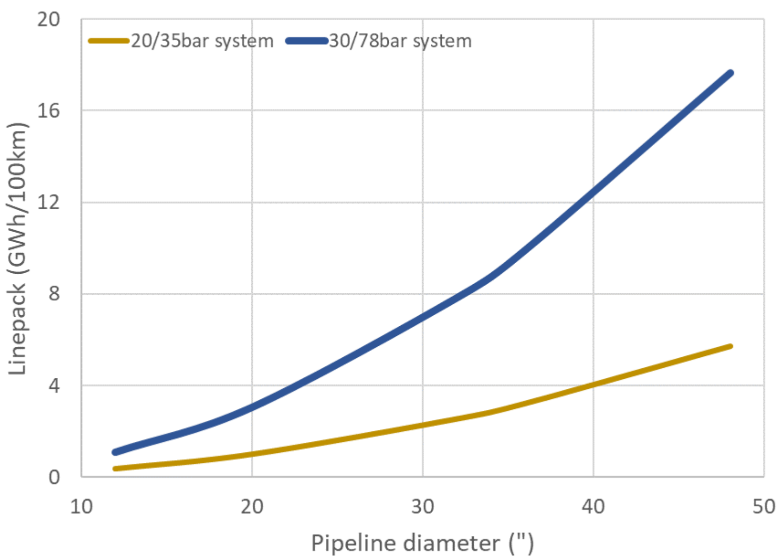

Figure 5. Illustration of the linepack potential: Possibility of storing gas between minimum and maximum pressure. A 36" piping system operated at 30/78 barg can have a linepack storage of approx. 10 GWh HHV/100km equivalent to 2.5tH2/km.

4.2 Indicative unit costs and capacities

Figure 6 shows transport cost estimates (DKK/kg) for three different pipeline diameters (16", 20" and 36" respectively) over a 250 km pipeline section. It is based on preliminary analyses on the assumption that the transmission pipelines will be operated between about 35% and 80% of full capacity. Updated analyses will include consequences of the general price development that we are currently seeing, where experience from ongoing gas projects shows that inflation and pressure on supply chains have had significant consequences on the investment costs. It

[2] Energinet and Gasunie: Pre-feasibility Study for a Danish-German Hydrogen Network (link)

should be noted that the utilization rate of the hydrogen grid (load factor, LF) is not determined solely based on the number of full load hours (FLH) at the electrolysis plants but could be increased through a hydrogen storage facility. The figure shows that there are significant economy of scale effects when transporting hydrogen, which ensures a lower cost per kg of transported hydrogen.

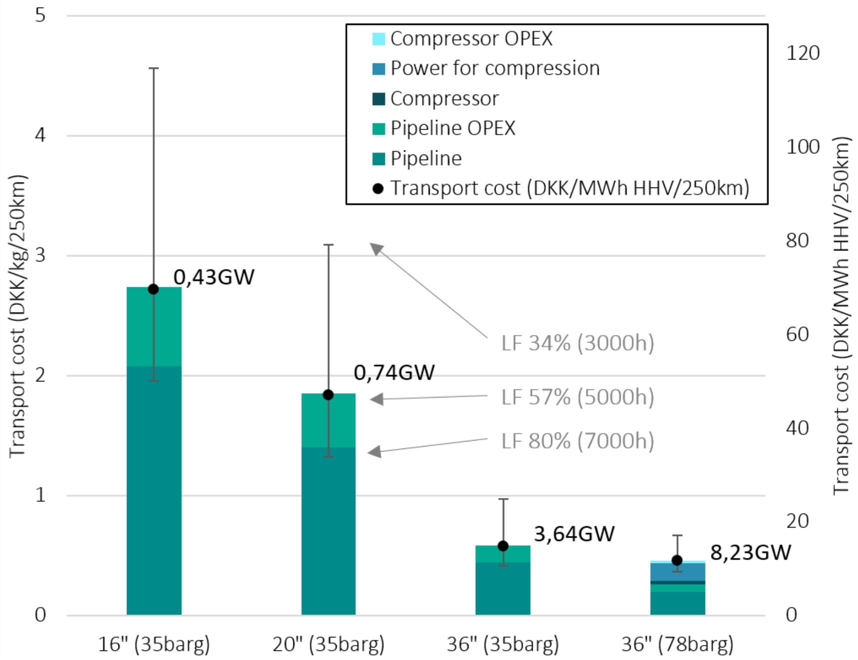

Figure 6. Preliminary calculations on hydrogen transport costs. There are significant economy of scale effects seen in hydrogen transport costs. Larger pipelines are needed to bring costs down over longer distances.

5. Cross-border activities

Energinet has entered into a cooperation agreement with the German Gas TSO, Gasunie Deutschland, which operates in Northern Germany, read more here. The intention is to ensure coordination and cooperation to realize a cross-border connection between green Danish hydrogen production and German and European demand for hydrogen.

One of the first concrete actions that we implement together is to apply for the project to be classified as a so-called *Project of Common Interest* (PCI) according to the EU TEN-E. With this status, it will be possible to apply for EU funding through the *Connecting Europe Facility* Fund. This allows for EU support of up to 50%, and Energinet has historically had good experiences with participating in these processes.

6. Next steps

The continued analyses in Energinet's feasibility study will include:

- Qualification of costs in the light of current economic developments
- Proposal for a market model and tariff structure for the transport of hydrogen
- Method for socio-economic profit calculation
- Screening of the economy in the alternatives examined

- Business model and financing analysis
- Screening of trace for new hydrogen transmission pipelines and conversion option for Frøslev-Egtved II
- Timetable for the establishment of new hydrogen transmission pipelines and conversion of Frøslev-Egtved II
- Preparatory dialogue with approval authorities on technical, planning and environmental level

Energinet will invite you to a stakeholder dialogue meeting on 28 November, where we will share concrete preliminary results and have a dialogue to ensure that the study's prerequisites and results support the needs from stakeholders.

Energinet is working towards being able to present the conclusions from the feasibility study and make a recommendation by the end of March 2023. The recommendations will be based on whether there are socio-economic benefits from establishing hydrogen infrastructure. If the recommendation is to initiate a maturation project, this must be approved by both Energinet's Board of Directors and by the Minister for Climate, Energy and Utilities. We will work to ensure that a decision on the initiation of a maturation project can be taken relatively quickly after completion of the feasibility study.

Completion of a maturation project with presentation of a socio-economic business case and recommendation on establishment project is estimated to be completed in 1-1½ years.

Energinet will keep you informed about the progress of the feasibility study here. You are also always welcome to contact Steen Brostrup Knudsen (sku@energinet.dk), who is the project manager for the feasibility study.