ENERGINET

WINDS OF CHANGE IN A HYDROGEN PERSPECTIVE

PtX Strategic Action Plan

November 2019

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WINDS OF CHANGE- STRATEGY FRAMEWORK

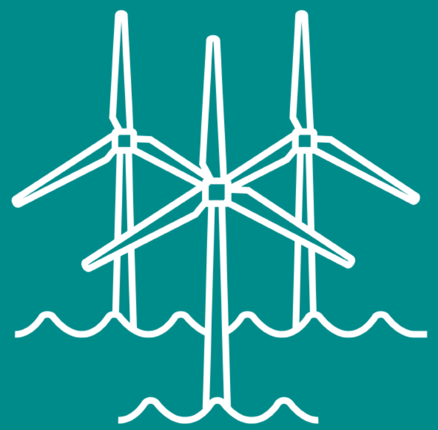
Energinet's Board of Directors has launched a new strategy 'Winds of Change ', which points to large-scale PtX contributing to Denmark's national climate goal of a 70% reduction in carbon emissions by 2030. The strategy forms the foundation for a strategic PtX action plan for how Energinet can support and accelerate PtX development in Denmark. The action plan relies on four principles, which make up the basis for Energinet's role in the implementation and wider diffusion of the technology:

- Ensure a clear division of roles with a distinction between monopoly activities and market-based activities.
- Ensure activation of demand-side response and utilisation of synergies.
- Work for framework conditions that underpin value chains and secure the green value of PtX products.
- Make knowledge and data available to the public.

The PtX action plan is a coordinated effort between Energinet's subsidiaries and requires close dialogue with external stakeholders, including RE producers , the PtX industry and national and European authorities. Energinet will collaborate with external stakeholders and authorities on the following topics:

- Identifying landing zones
- Developing market models and integrated infrastructure planning
- Creating incentives that ensure infrastructure utilisation
- Securing the green value of PtX products throughout the value chain.

KEY MESSAGES OF THE PTX ACTION PLAN



PTX IS KEY TO THE FURTHER DECARBONISATION OF THE ENERGY SYSTEM

In June 2018, the Danish Parliament signed an Energy Agreement, which set a goal of a fossil free society in 2050. The Social Democratic government has since launched a so-called “moon landing project“, aiming to reduce greenhouse gas emissions by 70% before 2030 compared to 1990 levels.

The ambitious climate goals should be reached in a socio-economic manner without jeopardising Denmark's high security of supply. Energinet has a particular responsibility in making sure that the green transition of the energy sector considers all aspects of the ‘Energy Trilemma', including green energy, security of supply and affordability. Energinet works every day to maintain the balance of the trinity while planning for a fossil free energy system.

A moon-landing project and the role of PtX

Over the past 30 years, Denmark has transformed its energy supply and renewable energy is now able to compete on market terms. To reach the target of a 70% reduction in green house gas emissions by 2030, we must continue the expansion of renewable energy production, increase the number of electric vehicles on the roads and accelerate electrification of buildings and industry. In the most optimistic scenarios, electricity will, however, only cover 60-70% of Denmark’s total demand for energy.

In order to make the ‘moon landing project’ successful, we need to find ways to decarbonise the remaining 30-40% of the energy sector. These comprise sectors that are carbon-heavy and costly to electrify, such as heavy-duty vehicles and certain industrial processes. Hydrogen and PtX will play an important role in decarbonising these sectors and ultimately be instrumental in reaching the 70% reduction goal by 2030.

We cannot do it alone

Energinet was an important player in the first half of the green transition. Especially when it comes to efficiently integrating large volumes of renewable energy from solar, wind and biogas sources into the system while safeguarding well-functioning energy markets.

However, with PtX, we are facing a situation where new value chains will emerge and potentially result in a multi-fold increase in electricity consumption in Denmark. This means that it is necessary to rethink the traditional approach to infrastructure development. If large-scale offshore wind is to be connected to the demand side via PtX, a parallel and simultaneous development of offshore wind production from the North Sea, electrolysis and PtX production must take place while ensuring there is a market for PtX products.

With this action plan, Energinet will develop several initiatives to support the development of PtX value chains in Denmark. We want to actively collaborate with potential producers, technology suppliers and not least consumers in future PtX value chains. Energinet is ready to form partnerships and contribute to a national effort to promote PtX, should it become a political priority.

Danish strongholds within sector coupling

Denmark has several comparative advantages, which have increased the interest in PtX in Denmark in recent years.

- Competitive power prices, great RE potential and a strong electricity grid that is well-connected to other countries
- An efficient gas system with access to gas storage facilities that are suitable for hydrogen storage
- A leading position within biogas, which can be utilised in the production of carbon-based PtX products
- A comprehensive district heating system which, in relation to energy conversion, ensures that the value of surplus heat is captured.
- A DataHub and efficient handling of data that underpins the emergence of new, green business models.

PTX PERSPECTIVES IN DENMARK TOWARDS 2030 – AND BEYOND...

PtX has the potential to contribute considerably to Denmark's 70% reduction goal by 2030 and a significantly greater potential beyond 2030.

Energinet's 'System perspective 2035' analysis provides indicative estimations of how the production of green fuels, including PtX, will contribute to CO2 reduction in 2030 and 2035.

The 70% target is very ambitious, and the realisation of this target requires a massive and combined effort that entails conversion of electricity production, significant electrification and development of PtX for production of electrofuels, which are considered difficult to electrify.

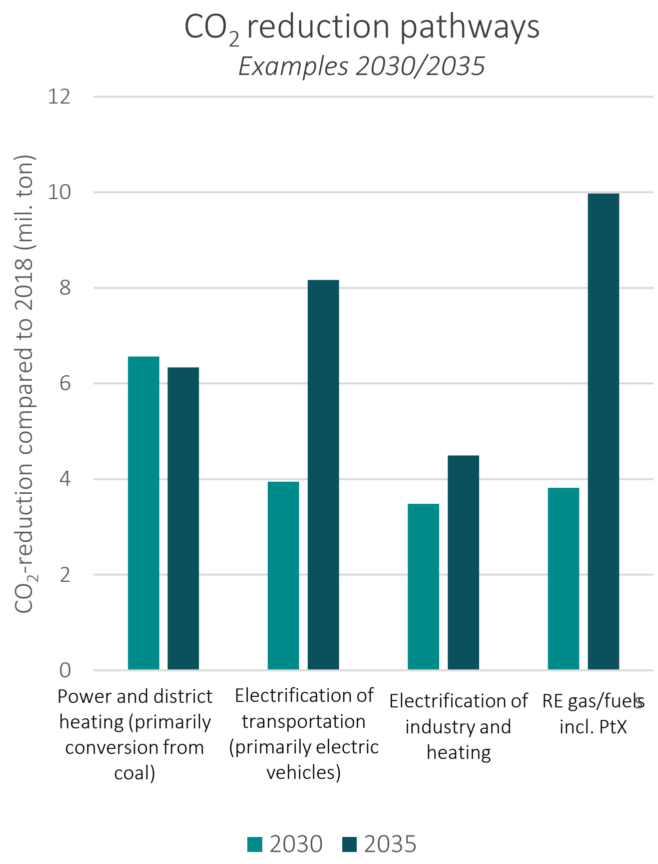
The figure on the right illustrates a preliminary assessment of the CO2 effect resulting from a conversion of coal power, electrification and production of green fuels, including PtX, in 2030. It shows a CO2 reduction of approximately 4 million tonnes from green gases and fuels, including PtX, assuming a direct contribution from electricity of just under 1.5 million tonnes with the rest coming from biogas and biomass. Towards 2035, this potential could be magnified and lead to a CO2 reduction of approx. 10 million tonnes with the direct contribution from electricity making up approximately half.

Green gases and fuels can either be consumed domestically or exported to other countries and thereby directly replaces fossil fuels. When it comes to large-scale production of green gases and fuels, access to carbon is a constraining factor, which is why there should be focus on utilising all available carbon sources, both well-known and untested. Biogas is one of the known technologies for the provision of carbon and some of the potential from straw is included in this calculation.

The challenge for green gasses and fuels towards 2035 is to commercialise new technologies that generates access to carbon. This includes thermal gasification or CCU (Carbon Capture and utilisation) from large CO2 emitters such as cement plants. In the meantime, the political target of a 70% reduction by 2030 poses several dilemmas for the development of PtX in Denmark.

PtX for fuels used for road transport in Denmark and domestic air and sea transport will count towards the Danish 70% reduction target. Production of PtX fuels such as, for example, fuel for international flights and ammonia for international sea transport is also expected to be major, important markets in relation to the PtX industry. While this will contribute to decarbonisation in Europe and internationally, it does not count towards Denmark's national climate commitment.

There should therefore be focus on avoiding a too narrow approach in the national 70 % reduction goal, since it could divert attention from those sectors that are not counted towards Denmark's national climate target, however, has great potential for decarbonisation beyond 2030.



PTX GUIDING PRINCIPLES

The emergence of PtX leads to new value streams that require coordination and a clear division of roles. What is Energinet's role?

Fundamentally, PtX is sector coupling or indirect electrification, which translates to the conversion of renewable electricity into electrofuels as replacements for fossil fuels.

Sector coupling through PtX is still under development and characterised by consumption and production through a number of value streams, such as:

- RE electricity production from wind and solar sources.
- Hydrogen production from electrolysis.
- Preservation of the green value throughout the value chain from RE production to end consumer.
- Carbon for the production of more advanced PtX products (hydrocarbons).
- Infrastructure for storing and transporting new products and value streams
- Surplus heat from conversion of energy.

The above mix of well-known and new value streams must be brought together. The path to reaching accelerated PtX development depends more on securing scale and commercialisation as opposed to investing in R&D for each individual component of the value chain. This will not happen automatically as no participant comprises he the entire value chain.

Coordination, cooperation and division of roles are therefore key to getting the pieces to fit together. As a result, Energinet has identified four guiding principles in relation to the action plan:

1. Energinet supports an appropriate *division of roles* between *Energinet as system operator and market participants operating on market terms.*

2. *The flexibility* of PtX must be utilised so it benefits the green transition.

3. Energinet provides *the right framework conditions with regards to* market and technical connections to the grid without favouring particular technologies.

4. Energinet participates in the public debate by *sharing knowledge* about PtX when it comes to technical and socio-economic aspects.

These four guiding principles are important because they provide a framework for defining the roles and responsibilities that are considered natural for an infrastructure operator to undertake and those that should be left to partners such as authorities and other participants.

DIVISION OF ROLES

Large-scale hydrogen transport and storage that ensures third party access: Independent infrastructure operators.

Electrolysis and use of hydrogen: Commercial activities.

Commercial participants throughout the entire value chain should be able to capture the green value.

RIGHT FRAMEWORK

Actively support the emergence of new value chains for PtX through appropriate framework conditions.

Cost-based payment for the use of infrastructure.

Document and maintain the green value.

Support technology neutrality and similar conditions or for large flexible consumers.

DEMAND-SIDE RESPONSE

Create basis for flexible use and exploitation of synergies.

Reduce the need for expansion of the electricity grid.

Assume a holistic perspective in relation to resources, existing infrastructure and demand options.

KNOWLEDGE SHARING

Sector coupling and its role in the energy system.

Technical and economic considerations and framework conditions.

International cooperation.

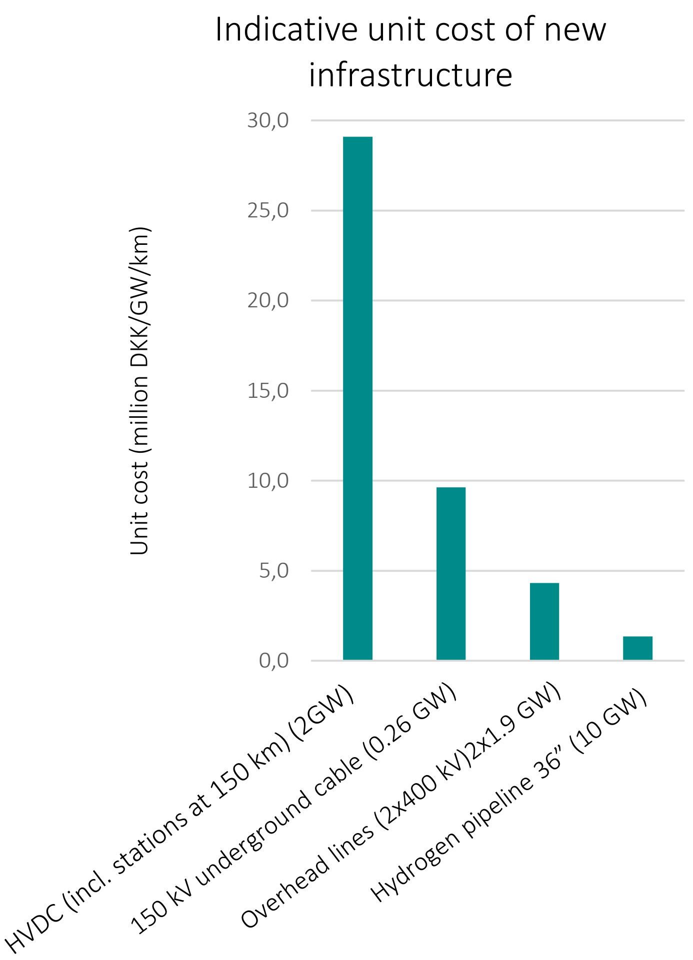
A STRATEGIC ACTION PLAN WITH BOTH PLANNING AND MAR

Historically, major public investments such as new infrastructure has begun with regulation and planning. Since then, optimisation and utilisation of infrastructure have been safeguarded through deregulation to a greater extent and the establishment of appropriate market conditions, leaving it to natural competition to determine how resources are best allocated. This development is observed across a wide range of major infrastructure investments, including ports, bridges, railways, and within the energy sector, such as electricity, gas and district heating.

- Electrolysis and PtX have broader purposes than creating a new form of end use from electricity generation; rather, it concerns converting electrical energy to other forms of energy.
- Fundamentally, electrolysis and PtX entail direct indirect electrification through sector coupling. Electricity is converted (consumed) not directly to its final energy form like e.g. heat or transport work – but to chemical energy storage in molecules. In this way, energy can be stored and transported over long periods in a relatively simple and cost-effective way and subsequently used for different purposes.
- The hydrogen molecule is a central energy carrier for PtX. However, it requires infrastructure in the form of pipes and underground storage facilities in order to be transported and stored efficiently in a large scale. Alternatively, hydrogen end use must match production and be located near the electrolysis plant or further refined to PtX products that can be transported. The latter may require other types of infrastructure for transportation of e.g. CO_2.
- Electrolysis can potentially also reduce the need for new electricity infrastructure, especially if electrolysis plants are located near (large-scale) connection points, injecting wind and solar generation into the collective electricity grid.
- Infrastructure for transporting energy has very different technical properties and widely different unit prices (million DKK/GW/km). Due to the high energy density of hydrogen, hydrogen pipes can transport much more energy per DKK invested than similar AC or HVDC solutions and are not affected by congestion problems in the same way as the AC cable. At the same time, expectations are:
  - that there will be a need for energy transport in the GW magnitude (up to +10 GW), which hydrogen infrastructure allows,
  - that it may be possible to connect Denmark to a European hydrogen infrastructure and to a Danish hydrogen storage facility, which will provide flexibility between renewable energy production and hydrogen production,
  - that, as all forms of PtX require conversion from electrical energy to hydrogen, it is the obvious option to consider all possibilities for using hydrogen as a primary energy carrier over investing in major expansions of the existing AC cable on land.

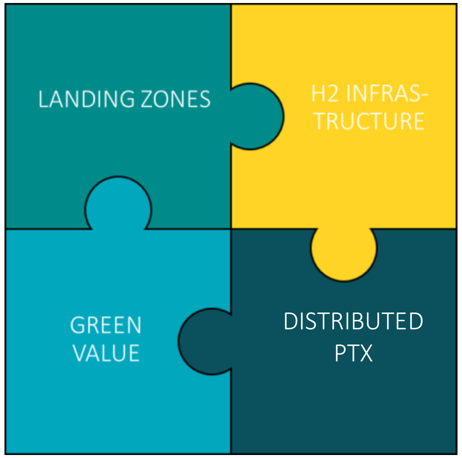
In conclusion, electrolysis and PtX can be seen as ground-breaking energy technologies that have the potential to significantly affect energy infrastructure in Denmark. The PtX strategic action plan therefore both includes actions related to the overall planning and actions related to adapting existing market conditions for the electricity system, in particular, to embrace electrolysis, as a sector-coupled and price flexible electricity consumption.

Four areas are estimated to have particular importance when it comes to supporting large-scale PtX and large-scale offshore wind generation. These four focus areas will be presented on the next page.



PTX – A PUZZLE WITH FOUR INTERDEPENDENT PIECES

The implementation of the PtX and large-scale offshore wind strategy is best supported by assuming a holistic perspective and by initiating parallel actions in four focus areas. These focus areas should not be seen as a ' buffet ' of single alternatives, but rather as four interdependent pieces of a puzzle.



Landing zones

Landing zones make it possible to receive GW-sized renewable electricity and reduces pressure on the electricity grid on land.

1. Clarify limitations and definition of landing zones
2. Determine whether hydrogen infrastructure is a prerequisite for landing zones
3. Identify the demand for and value of landing zones for the overall system
4. Identify possible locations for "first landing zones“.

Hydrogen infrastructure

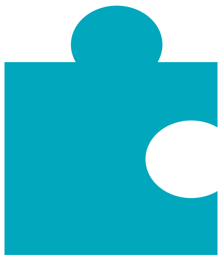
Hydrogen infrastructure allows for transport and storage of hydrogen through a decoupling – both timewise and geographically – between production and consumption of hydrogen.

1. Analyse demand for hydrogen infrastructure
2. Regulation of hydrogen infrastructure
3. Planning in accordance to the outside world
4. Identify possibilities for conversion of existing gas infrastructure

Distributed PtX

Distributed PtX with small electrolysis capacities is fundamental for kickstarting PtX development as regards to access to carbon sources.

1. Investigate need for more flexible electricity grid products for transmission and distribution
2. Maintain green value across the energy system
3. Promote a carbon strategy that ensures that scarce carbon sources are used where they create the most value



Green value

Maintaining the green value of the product throughout the value chain – in regards to energy conversion and transport systems – ensures that the end user of PtX products receives value equivalent to the additional cost of the green end product .

1. Obtain clarification of green certifications from authorities
2. Clarify European and international certification rules in relation to e.g. Renewable Energy Directive

BACKGROUND MATERIAL

ANALYSIS OF FOREIGN HYDROGEN AND PTX TRENDS (1/2)

In recent years, hydrogen and PtX have gained considerable momentum in Denmark as well as internationally. Various countries and regions see different potential for supply and demand of green hydrogen. Common to all is that a decrease in RE prices and focus on the green transition is driving this development at a historical pace. The following sections look at global hydrogen trends with special attention on hydrogen infrastructure and the opportunities it creates for Denmark.

Europe

There is an apparent interest in hydrogen in Denmark's neighbouring countries. Norway, the Netherlands and Germany have already announced political ambitions for hydrogen and formulated or drafted national strategies. Those strategies have specific plans for the production of green and blue hydrogen and supporting hydrogen infrastructure. The Netherlands, Germany and France aim to introduce the first +100 MW electrolysis facilities within 2-3 years. It is worth noting that electricity and gas TSOs are directly involved as investors in these projects. In contrast to Denmark, there is an existing demand for hydrogen in the industrial sectors in both the Netherlands and Germany.

Several European countries have created dedicated research funds for hydrogen technology. In Germany, for example, 1.5 billion euros have been allocated for the development of electrolysis and fuel cell technology over a ten-year period.

In 2019, the Dutch electricity and gas TSOs presented an infrastructure plan for 2050, which covers nationwide electricity, methane and hydrogen grids in the Netherlands and Germany.

The UK has launched a project called H21, planning to convert a large natural gas distribution area to pure hydrogen before 2034. The project involves the production of blue hydrogen from natural gas and storage of CO2 in the North Sea (see explanation on the next page). The long-term plan is to produce green hydrogen from electrolysis.

At an EU level, hydrogen is about to enter the IPCEI list (**I**mportant **P**rojects of **C**ommon **E**uropean **I**nterest), which could kick-start the sector in several ways. Projects on the list may be exempted from competition rules, for example, which could make the technology more accessible.

Australia

Australia is an obvious location for hydrogen production due to the abundance of solar and wind resources and limited demand for electricity. In 2019, the Australian government presented a roadmap for how Australia can become a leading producer and exporter of hydrogen.

The Australian roadmap for hydrogen is divided into three phases towards 2028.

1. Demonstration phase, in which small plants produce hydrogen for use in the transport sector.
2. Larger quantities of hydrogen are produced and injected into the natural gas grid.
3. Export of hydrogen via ships to a global hydrogen market.

Due to the significant potential, Australia has already made trade agreements with the industrial sector in Japan, for example. Hydrogen export requires the substance to be liquefied by cooling it to -253 °C before it can be transported via ships. This process causes an energy loss of 30-40%, but, on the positive side, it allows hydrogen to be sold on a global market.

Asia

Japan and South Korea have high ambitions for hydrogen. Both countries want to create actual hydrogen societies and have made political commitments to use hydrogen in a large part of the industrial and transport sectors. However, both countries have limited RE resources and are therefore dependent on the import of green hydrogen. As a result, Australia is planning on making Japan and South Korea its first main export markets.

ANALYSIS – FOREIGN HYDROGEN AND PTX TRENDS (2/2)

International trends and consequences for Denmark

As previously described, the Netherlands and Germany have far-reaching plans for hydrogen and hydrogen infrastructure. Denmark ought to pay particular attention to the plans to build hydrogen infrastructure south of the Danish border.

This creates an opportunity to transport Danish-produced hydrogen to the Netherlands and Germany via a regional hydrogen network and, in the long term, via a more extensive European hydrogen network. It is particularly interesting that both the Netherlands and Germany foresee a need to import hydrogen due to their limited national RE potential.

Import of hydrogen and PtX products to Europe

Whether the import of liquid green hydrogen to Europe becomes relevant depends on whether low hydrogen production costs in e.g. Australia offset the cost of transporting hydrogen and converting it into liquid hydrogen, which is a highly energy-intensive process.

Hydrogen can also be converted into ammonia, which has a number of advantages. Firstly, ammonia can easily be produced where the production of hydrogen takes place, since nitrogen can be extracted directly from the air. Secondly, a global value chain for ammonia already exists, along with a demand for ammonia from the chemical industry. Moreover, there is an increasing demand for ammonia as a fuel in the shipping industry.

Liquid PtX products, such as aviation fuel and methanol, have a number of advantages. Those include existing demand and the fact that it is easy to handle and cost-effective to transport. Access to carbon, however, limits the production of PtX products. If this barrier can be overcome, it is highly possible that methanol and other PtX products, that require carbon, can be produced in large quantities and at low costs outside Europe.

Green hydrogen production costs

The production costs of green hydrogen have a reduction potential of 80% by 2030 according to the research institute Bloomberg New Energy Finance. This requires electrolysis plants to reach industrial scale and a continued decrease in the costs of solar and wind power production.

Blue Hydrogen as an alternative

Blue hydrogen is derived from natural gas where CO2 is captured and stored underground. The immediate benefit of blue hydrogen is primarily that it is more affordable to produce in the short term, making it more scalable compared to green hydrogen. Whereas green hydrogen requires massive expansions of wind and solar facilities in order to reach scale, blue hydrogen can be produced in large volumes much faster. Today, close to 1/5 of the EU's natural gas consumption is used to produce hydrogen. The so-called grey hydrogen, that excludes CO2 capture, is consumed in various industrial applications. It is therefore important that Denmark and Energinet follow the development of hydrogen in Europe. On the one hand, blue hydrogen can become a direct competitor to green hydrogen. On the other hand, blue hydrogen can be instrumental in creating new value chains and infrastructure, thereby paving the way for green hydrogen in the long term.

IEA analysis on hydrogen

In June 2019, the IEA published the report "The Future of Hydrogen - Seizing today's opportunities ". The report presents seven recommendations on scaling up the production and use of hydrogen, and five of these concern key issues for PtX development. Those are:

- Position hydrogen in the long-term energy policy.
- Create commercial demand for pure/green hydrogen.
- Address first-mover barriers.
- Remove unnecessary regulatory barriers.
- Participate in international cooperation and monitor development.

DEMAND SIDE

Compared to other countries (e.g. Australia) with access to considerable RE resources, Denmark has the advantage of wind resources being located close to large industrial hubs in Europe with Germany and the Netherlands being the most obvious export markets.

In the long term, hydrogen could be produced locally and transported via pipes, providing a more cost-effective mode of transport compared to shipping. However, it is uncertain whether production from the North Sea can sufficiently meet European demand, and therefore it may be necessary to rely on both import and local European production.

Denmark will not have sufficient carbon resources (presuming direct air will not suddenly become very affordable) to support a full transition of the aviation sector in Europe, for example. In Scandinavia, the volume of aggregate carbon potential is presumably extensive, but still currently unknown. The most probable scenario is that there will be a market for both local production and import.

Germany and the Netherlands are expected to see significant demand for hydrogen in the next few years. Consequently, from a Danish perspective, it seems obvious to export hydrogen via pipes to those markets. This, of course, will depend on when connecting hydrogen infrastructure to Denmark is ready. Denmark should be prepared to connect to a German/Dutch infrastructure network when it becomes available so that Danish hydrogen producers will have access to the industrial hydrogen markets in these countries. However, if this opportunity does not arise immediately, Denmark should consider other demand possibilities.

When hydrogen is exported to other countries, this benefits not only Danish companies. It also supports the green transition in the regions where the hydrogen is exported to. Today, consumption of hydrogen in the Danish industrial and transportation sectors is very limited. Until there is sufficient demand for hydrogen, it will be difficult to create large-scale PtX production.

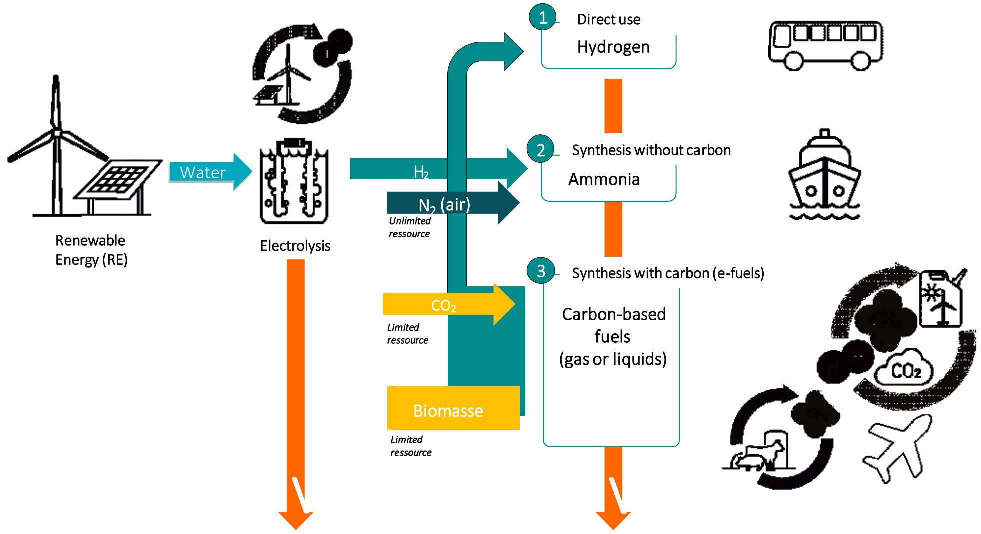
Therefore, the first market for hydrogen in Denmark is expected to be the heavy-duty vehicles sector (buses, garbage trucks, etc.) and PtX processing industry. In the processing industry, e-fuels would either replace or supplement existing fossil fuels such as petrol, diesel and jet fuel.

The production of e-fuels can be realised prior to the establishment of an international hydrogen infrastructure. There appears to be particular interest in and willingness to pay for e-fuels in the aviation sector, where a niche market is expected to emerge. In the meantime, access to cavern storage is likely to improve the viability of PtX plants. Establishing PtX production zones or clusters should be prioritised to keep infrastructure costs down.

When the demand for, for example, e-fuels allows for hydrogen infrastructure expansion, value chains can be optimised using cavern storage, among other things. Whenever financially viable, infrastructure should be located close to industrial hubs to ensure that hydrogen is used directly in high-temperature processes or other chemical processes that leave biogas to be used as building blocks in PtX production. This provides further opportunities to attract additional PtX industries and potentially expand the processing and chemical industries, which consume large amounts of hydrogen.

The overall driver of demand and elevated prices of green fuels

- Regulation, including EU regulation, requires the blending of green fuels into fossil fuels, which creates a market and a willingness to pay a premium price for green energy products.
- Expectations for additional regulation and more limitations on CO2 emission create expectations of an increased demand for green energy products. These expectations create a great deal of activity as many participants begin to prepare for this scenario.



There are three overall applications for green hydrogen

- Direct use of hydrogen, e.g. fuel for local transport, buses etc., processing industries, steel production, chemical production, possibly domestic heating in Germany and the Netherlands.
- Green fuel in the form of ammonia for large-scale energy consumption, where carbon is a limiting factor, e.g. maritime transport, chemical production, fertilizer production.
- Green fuel, where carbon-based fuels are particularly suitable, in particular aviation fuel, chemical production and industry.

GREEN VALUE

From a socio-economic perspective, PtX with sector coupling, keeping the green value, improves the carbon footprint of difficult-to-electrify-sectors, such as transportation, agriculture, industry and heating.

From a market perspective, the value of green hydrogen is pivotal for green business models. Green fuels are more expensive than fossil fuels that are subject to inexpensive CO2 quotas and small or no carbon taxes. Producers of green fuels rely on additional income beyond the 'equivalent fossil energy’. Additional income could derive from a greater willingness to pay for the green product. The green value is real; today, the value of green methanol is double the value of the fossil equivalent, for example. The premium value of green products derives, among other things, from regulatory requirements for the blending of green fuels and expectations of prominent market participants that more regulation will follow.

EU’s new RE directive (RED II) defines green energy products. If energy is used for transportation, RED II sets out additional requirements to ensure that the electricity source used for electrolysis is actually green.

The willingness to pay for hydrogen in the transportation sector is expected to be greater if green value is documented. As a result, documentation of green value is essential to ensure a positive business case in the transportation sector.

Under RED II, the green value of hydrogen-based transportation fuels can be documented in three ways. In a Danish context, the first two ways are particularly interesting:

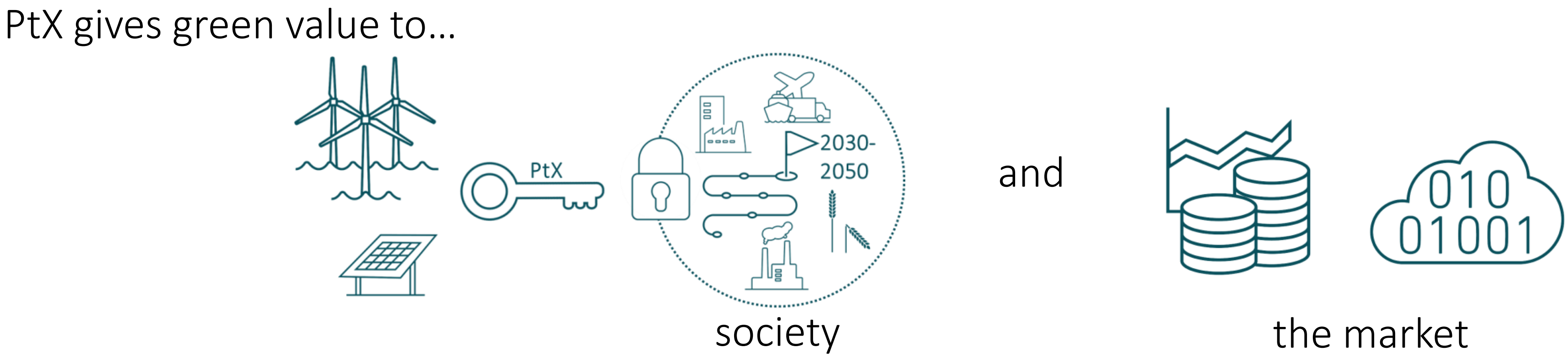
1) In relation to landing zones, it is possible to generate 100% green electricity with an upstream model. Although electricity generated from a wind farm with no underlying interconnectors is considered green, physically speaking, there are still regulatory challenges. Requirements for additionality mean that wind turbines must be established after the electrolysis plants, which is difficult in practice.

2) For distributed PtX, the most obvious solution is to ensure coherence when it comes to time and location between RE production and consumption in an electrolysis plant. This could be realised using data from Energinet’s DataHub. However, this solution is challenged if the European Commission chooses to wait until 31 December 2021 to adopt a delegated act that specifies compliance with RED II regulation.

Energinet is currently doing a Digitalization sprint, 'Project Green Coin', which aims to demonstrate that it is possible to develop a solution that complies with the requirements under RED II. This test is more restrictive than what is expected to be required under the delegated acts presented by the European Commission in 2022.

3) The third and last way to document green value under RED II is considered a fallback solution. In this case, the percentage of green hydrogen in an electrolysis unit connected to the power grid is determined by RES-E two years prior. In Denmark, RES-E was 60.4% in 2017, which means an electrolysis plant connected to the power grid in 2019 produces 60.4% green hydrogen. This approach undermines the business case for PtX due to low efficiency. It also does not create coherence between electricity generation and consumption, failing to facilitate sector coupling and exploitation of synergies. This means there will be both green and non-green hydrogen in the grid. The question is whether this has an impact on hydrogen market value. The good thing about this approach is that Denmark has an existing comparative advantage and there are no implementation barriers.

In addition to using data and digitalisation for certification, access to large amounts of data creates a green market value because it allows the market to apply detailed geographical energy data to document green value chains and other products to end customers.



ENERGY TRANSPORT
– CAPACITY COSTS AND SELECTION OF ENERGY CARRIER

PtX and large-scale offshore wind resources lead to greater requirements for and capabilities of the overall energy system. Additional offshore wind capacity of approximating 10 GW is anticipated in the long run. This goes far beyond the *total maximum load* of the Danish electricity system today.

Assuming large-scale offshore wind and PtX capacities are developed in arbitrary locations and integrated into the power grid, causing expansions of the AC grid, system changes will not be gradual or slow. Instead, very large, incremental expansions are expected with a long-term need for additional 400 kW overhead line systems – or other electricity transmission facilities with similar capacity – between grid connections for offshore wind and major consumption hubs.

When it comes to PtX, electrical energy must always be converted into hydrogen. It is therefore natural to consider if energy from offshore wind – after being brought onto land – should be further transported as electricity or hydrogen.

The various options for transporting large volumes of energy have very different technical properties as well as widely different unit prices (DKK million/GW/km), as depicted in the table at the bottom of this page.

AC grid solutions, both overhead lines and cables, will cause a need for redundant connections to maintain the security of supply in order to avoid bottleneck issues in the grid. The impact on the landscape will be considerable, regardless of whether a cable or an overhead line solution is chosen, and experience shows that it is difficult to obtain permits for and public acceptance of these types of infrastructure.

Transporting hydrogen via pipes has significantly lower unit costs. This difference is caused by the very high energy density of hydrogen. Unit costs are actually so low that it is more cost-effective to establish a large hydrogen pipeline with a 10 GW capacity than to establish one new 2x400 kW overhead line or a single HVDC connection – which would even have significantly lower capacity. This means that it can be advantageous to go for a hydrogen solution, even if there is no need for the entire capacity from the beginning.

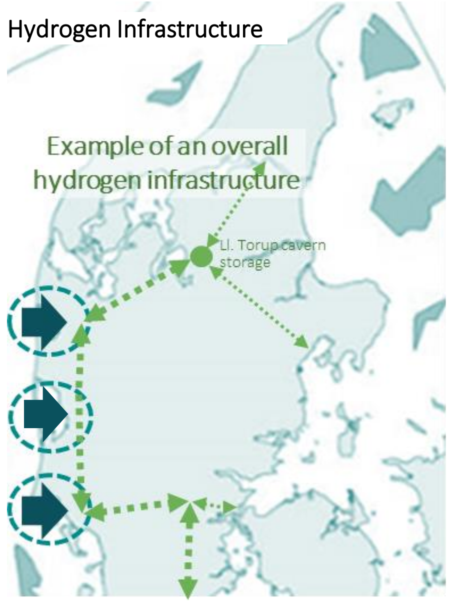
Hydrogen infrastructure offers a number of additional opportunities.

- It will be possible to connect Denmark to a European hydrogen infrastructure when or if it is established in Germany and the Netherlands.
- It will be possible to connect electrolysis plants to a Danish hydrogen storage facility, which will allow flexibility between hydrogen production based on renewable energy and hydrogen consumption for further processing.

Since PtX and large-scale offshore wind involves GW-scale capacity, a decision must be made at some point as to the mode of transportation for the large amounts of energy in the system.

In conclusion, hydrogen should be the obvious choice when deciding on the primary energy carrier to avoid big expansions of the existing onshore AC grid. Furthermore, the energy conversion opportunities that this solution creates should be taken into account.

Types of infrastructure	Capacity (GW)	Unit costs (million DKK/GW/km)
HVDC (150 km incl. conversion)	2	29.1
150 kV underground cable	0.26	9.6
Overhead lines 2*400 kW	2 * 1.9	4.3
Hydrogen pipeline 36"	10	1.4



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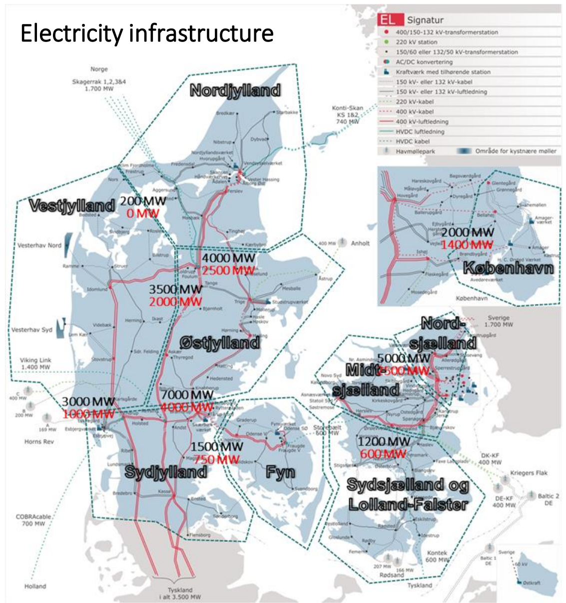

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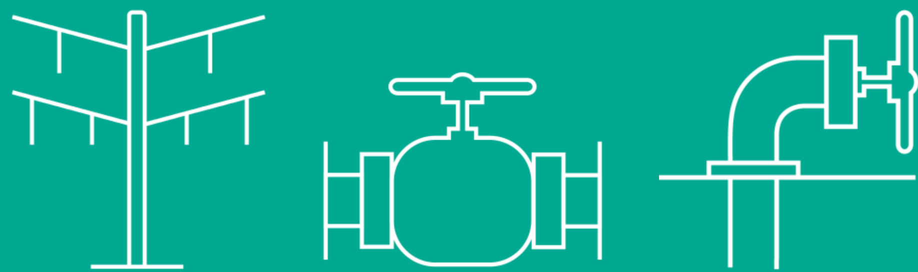
DETAILS OF THE ACTION PLAN



THE FOUR MOST IMPORTANT PIECES

These four focus areas are expected to be the most important drivers for supporting the implementation of Energinet's strategic vision on PtX and large-scale offshore wind.

Landing zones

- A 'buffer and conversion zone' for large-scale injection of wind (or solar) energy into the collective AC grid.
- Comprises, as a minimum, electrolysis, but could also cover local PtX processing industries if there is no infrastructure to transport hydrogen further on.
- Is expected to be simpler and faster to implement (also as a sandbox) than a fully compatible PtX market design.

Hydrogen infrastructure

- Can create more demand opportunities for hydrogen – both as a final and intermediate product – and both nationally and internationally.
- Instead of perceiving hydrogen infrastructure as something that will occur when PtX has reached a certain scale, hydrogen infrastructure could also be an enabler for large-scale electrolysis and PtX.

Distributed PtX

- PtX plants outside landing zones
- The foundational driver for scale-up of PtX development and the local interaction between distributed resources; particularly carbon sources.

Green value

- The premium value of green products is guaranteed by regulatory requirements such as blending obligations for green fuels, among other things. The 'green value' should be maintained all the way through the energy system, from when the energy is mixed, transported and stored to when energy is converted from one form to another.

LANDING ZONES

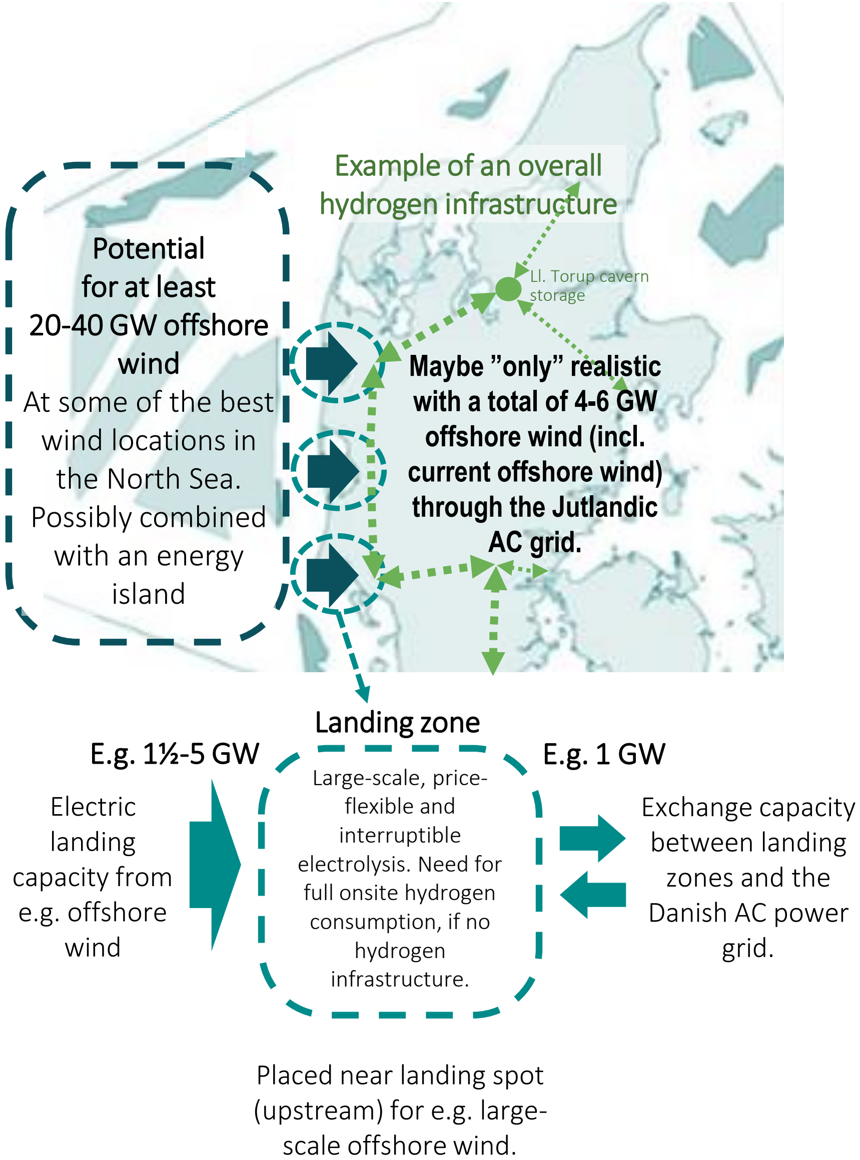
The concept of landing zones is under development, and the following definitions are therefore preliminary. One possible definition is that a landing zone is a defined area, which is located upstream electrically of a large influx of fluctuating, renewable electricity (wind and solar power) that serves as a 'buffer' between large-scale RE electricity generation and the remaining Danish AC power grid. The zone is characterised by having a large 'landing capacity' for renewable electricity compared to the typical exchange capacity in the remaining electricity grid. In addition, considerable price-flexible/interruptible sector-coupled electricity consumption will take place in the zone. Initially, sector-coupled consumption is realised with electrolysis, which facilitates utilisation through conversion of incoming renewable electricity, also in periods when the influx of renewable electricity exceeds the designed exchange capacity in the rest of the electricity grid. The overall concept of landing zones is illustrated in the bottom part of the figure on the right.

The concept is meant as a potential tool to ensure – also in the short term – that it is possible to integrate large amounts of wind and solar power into the Danish energy system compared to the realistic/economic expansion limitations of the electricity grid. When landing zones are combined with electrolysis/PtX, it also provides the possibility of contributing to the decarbonisation of carbon-heavy sectors such as transport and industry in Denmark and within the EU. This is fundamentally the most supporting argument for PtX.

When the electrolysis conversion takes place inside a landing zone with close access to the RE source, the demand for expansions or construction of new electricity infrastructure is reduced. It also helps market participants maintain the green value of the hydrogen produced– both in relation to RED II and to end customers who want a bullet-proof and simple green product. Most of the time, when electricity is sufficiently inexpensive for electrolysis to run, it will run upstream from specific RE sources. Green electrons becomes green molecules.

A particular challenge for large-scale electrolysis/PtX is to find demand for hydrogen (as an intermediate or final product). Hydrogen is difficult and expensive to store and transport in small volumes (pressure tanks). Developing large-scale hydrogen demand locally that matches ongoing hydrogen production from electrolysis in the landing zone could thus prove to be a significant 'chicken or the egg' issue. For large-scale, fluctuating hydrogen production, cavern storages and pipeline infrastructure is a considerably more efficient and inexpensive solution. A cavern storage facility can provide an inexpensive hydrogen buffer, which can even out temporary differences between production and consumption of hydrogen. A pipeline infrastructure can inexpensively and efficiently connect landing zones with cavern storages and potentially hydrogen demand centres (e.g. the PtX processing industry) – and possibly a global hydrogen infrastructure which, based on announcements from neighbouring countries, may soon become a reality. The figure on the right illustrates an example of a hydrogen infrastructure network in Jutland.

Assuming there is no hydrogen infrastructure available from the beginning, proximity to gas networks and/or CO2 sources will be important in supporting local hydrogen demand for the PtX processing industry, whereby hydrogen is upgraded to carbon-based fuels. Proximity between landing zones and demand for district heating could help ensure that surplus heat from the electrolysis production and local PtX processing is utilised.



ACTIONS – LANDING ZONES

The following initiatives should be implemented to support Denmark's development of large-scale offshore wind and large-scale PtX in landing zones:

Initiative	Comments	Deliverables	Internal project owners	External collaboration partners
Develop a concept for landing zones - Definition of landing zones. - Market model for participants (producers and, if relevant, consumers) in landing zones. - Technical requirements for interaction between landing zones and surrounding public electricity grid. - Regulation and framework conditions; including tariffs for participants in the landing zone.	These are, in fact, several closely linked sub-assignments. The term landing zone is under development, and it is therefore only possible to provide preliminary descriptions and overall headlines. Concepts will be different, depending on whether there is sufficient demand for building hydrogen infrastructure, or whether hydrogen must be used locally parallel to production. Developing the landing zone concept, focus must be on implementation and on providing a cost-based incentive structure for participants in the zone (producers as well as consumers) that makes it attractive to be in the zone. At the same time, steps must be taken to ensure that the zone is well incorporated into the remaining electricity system.	Develop concrete concepts for landing zone models. Concepts must include assessments of implementation viability in relation to regulation, system operation, energy policy compatibility and suggestions for framework conditions/connection principles. Concepts must be so specific that they can be used for high-level dialogue and provide basis for decision-making in a subsequent implementation effort.	Electricity System Operator, Gas TSO	Input from participants in PtX projects where Energinet participates; The Danish Energy Agency
Monitoring and coordination between landing zones, hydrogen infrastructure and hydrogen demand. *The initiative largely overlaps with 'Clarification of the need for hydrogen infrastructure' under Hydrogen infrastructure – and should be carried out in close coordination with this.*	An analysis of whether hydrogen infrastructure is a prerequisite for large-scale electrolysis/PtX should be made. To what extent are market participants ready to invest in electrolysis if hydrogen infrastructure is available and if it is not? And how does demand for hydrogen play out in both scenarios?	An indicative market assessment of the potential for electrolysis and hydrogen consumption in Denmark (or for exports) with and without hydrogen infrastructure.	Electricity System Operator, Gas TSO, Gas Storage Denmark	A broad sprectrum of (potentially commercial) electrolysis/PtX stakeholders in Denmark; The Danish Energy Agency
Identify possible locations of first landing zones (continuation of previous initiative).	Electrolysis (and potentially additional industry) in a landing zone has a large number of potential value streams – and costs – which must be considered collectively in order to assess the advantage of different locations. Focus is primarily on the technical and financial aspects of electricity and gas, but also on the basis for ensuring access to heating; geological options; local/municipal anchoring; and stakeholder value/interest.	Identification of possible geographical locations for landing zones and, if relevant, separate zones for PtX processing industry, assuming hydrogen infrastructure is available. Should serve as concrete input for further dialogue about large-scale electrolysis/PtX in Denmark and the location hereof.	Electricity System Operator, Gas TSO	Inclusion of a large number of potential public and private stakeholders within PtX in Denmark.
Maintain the green value of hydrogen, also in its use as transportation fuel, to comply with RED II blending obligations, among other things.	It is going to be important for many PtX business cases that hydrogen is 100% green and can be used in all contexts. There could be special circumstances related to certification in the case of landing zones with connection to hydrogen infrastructure.	The initiative is handled under *Green value*		The Danish Energy Agency and the Danish Ministry of Climate, Energy and Utilities

HYDROGEN INFRASTRUCTURE

Hydrogen infrastructure covers gas pipes and gas storage facilities for transport and storage of pure hydrogen. From an infrastructure perspective, it would make sense to convert electricity to molecules, which can be handled in gas infrastructure. Molecules have high energy density, which makes them very easy and more cost-effective to transport and store in large volumes. Intelligent and integrated hydrogen infrastructure can therefore reduce the need for new electricity infrastructure.

In relation to the concept of landing zones, it is relevant to identify the possibilities of piped transport of pure hydrogen in combination with gas storage facilities. In Denmark, there is no industrial sector prepared to use large volumes of hydrogen today which would be a prerequisite to infrastructure investments. New demand should be created within transport, refineries and, in particular, within production of liquid fuels for it to be relevant to build new infrastructure for the transport and storage of green hydrogen.

The alternative to building an infrastructure that only supplies the Danish hydrogen industry is to establish export connections to Germany and the Netherlands. One advantage to this approach is the existing demand for hydrogen in some industries in these countries. Thanks to the presence of Danish storage facilities, a connection will also create demand-side response.

In both cases there is, however, a fundamental 'chicken or the egg' dilemma of who should build and own hydrogen infrastructure, what scale it should have and under which conditions it should be built. If this dilemma is not addressed, it may cause a delay in PtX development in Denmark or, in a worst-case scenario, development may never start.

Energinet's PtX action plan will look at the technical possibilities and limitations of establishing hydrogen infrastructure in Denmark, considering two options: 1) Converting parts of the existing natural gas grid for hydrogen transport or 2) establishing new and dedicated hydrogen infrastructure. If hydrogen infrastructure is established in Denmark, the role of Energinet could be expanded from ownership and operation of electricity and natural gas infrastructure to also include hydrogen infrastructure.

ACTIONS – HYDROGEN INFRASTRUCTURE

Initiative	Comments	Deliverables	Internal project owners	External collaboration partners
Energinet will work to clarify the need for hydrogen infrastructure (pipes and storage facilities). This entails, among other things, creating scenarios for hydrogen consumption in Denmark with and without access to hydrogen infrastructure. *The initiative overlaps with the landing zones initiative – and is to be carried out in close coordination.*	It is difficult to imagine that production and consumption of large volumes of hydrogen will happen simultaneously and at the same location even if optimal. In other words, a need for both transportation and storage of hydrogen is expected in Denmark, which, as a nation, aspires to realise its climate ambitions in 2030.	• Energinet must engage in partnerships with potential participants in PtX value chains with the intention of developing scenarios for when and to what extent there will be a need for hydrogen infrastructure. • Energinet must use these scenarios as input for the analysis assumptions.	Electricity System Operator, Gas TSO, Gas Storage Denmark.	Commercial participants, e.g. Ørsted, Vestas, Siemens, Haldor Topsøe, the Danish Maritime Industry, etc.; The Danish Energy Agency and the Danish Ministry of Climate, Energy and Utilities
Energinet will look at how hydrogen infrastructure should be regulated. In order to understand the role of Energinet, we will engage in dialogue with our owner (*The Ministry of Climate, Energy and Utilities of Denmark*) to define criteria for when hydrogen infrastructure should be regulated and subject to third party access.	Energinet is not necessarily the obvious owner of hydrogen infrastructure. At the moment, there is no legal basis in the legislation. Establishing criteria for ownership provides a better foundation for arguing when Energinet can create value as owner of hydrogen infrastructure.	• Energinet will, in cooperation with our owner, set up criteria for when hydrogen infrastructure should be regulated as a natural monopoly in order to clarify a potential role for Energinet.	Group, Gas TSO, Gas Storage Denmark.	The Danish Energy and the Danish Ministry of Climate, Energy and Utilities, with input from a broad spectrum of Danish stakeholders.
Energinet will monitor the development of our neighbouring countries and pay particular attention to plans for hydrogen infrastructure in Germany and the Netherlands.	Energinet needs to address the regional and global trends for hydrogen and PtX in order to understand which value chains may arise within and outside Denmark's borders. In relation to this, obtain more knowledge about how infrastructure should be adapted to support new value chains and promote the development of hydrogen.	• Energinet should aim to engage in partnerships with German and Dutch TSOs (gas and electricity) in order to stay updated on and understand the development south of the Danish border.	Gas TSO, Gas Storage Denmark, Electricity System Operator	Foreign TSOs, interest groups such as 'Gas for Climate'
Technical possibilities and limitations in relation to converting part of the existing Danish gas infrastructure to hydrogen vs. building a new hydrogen infrastructure should be analysed.	There are no safety regulations for hydrogen infrastructure in Denmark today. This will take time to set up, and it would therefore be beneficial to start the process before there is a specific need.	• Energinet should develop conceptual technical models for establishing hydrogen infrastructure with the aim of obtaining cost estimates for different models. • Together with relevant authorities, Energinet should prepare safety measures regarding the establishment of hydrogen infrastructure.	Gas TSO, Gas Storage Denmark	The Danish Safety Agency and The Danish Energy Agency

PTX OUTSIDE LANDING ZONES – "DISTRIBUTED PTX"

The definition of distributed PtX primarily relates to the location of PtX, and PtX facilities located outside a *landing zone* is defined as *distributed PtX*. This concerns, for example, facilities located far from large landing zones with MW rather than GW-sized production.

These production facilities can be located almost anywhere in the country and assume all sizes, from hundreds of kW to hundreds of MW. As a result, these facilities will have widely different business cases.

The strategy behind distributed PtX should be to make it attractive to establish PtX facilities in all sizes and to ensure that all available value streams are utilised. This includes, but is not limited, to hydrogen. Production of heat, balancing of the electricity grid, optimisation of both upstream and downstream infrastructure, reduction of the climate footprint from CO_2 emitters by enabling the reuse of carbon are all examples of value streams that are created and should be utilised within distributed PtX.

Distributed PtX has the unique advantage that it can balance local electricity grids and deliver the same flexibility to the system as international connections and power stations. It also produces hydrogen locally, which allows hydrogen to be transported to a greater area in a short period of time and at a lower cost compared to PtX produced in a few, central landing zones that depend on nationwide infrastructure to reach all consumption hubs. With distributed PtX, small distribution networks for hydrogen transport could be established independently of each other, creating a more dynamic and market-driven basis for production and consumption. There are already several PtX projects in operation around the country, for example BioCat Roslev, HyBalance (illustrated in the picture below), Power2Met and the growing network of hydrogen stations, which produces hydrogen onsite using green electricity and electrolysis (Green Hydrogen/Nel/Danish/Hydrogen Fuel/Copenhagen Hydrogen Network). In addition, a number of PtX projects are in the pipeline in different parts of the country that Energinet is aware of but not involved in. These new projects' financial viability will depend on framework conditions, particularly the economic terms and conditions of the collective electricity grid.

HyBalance in Hobro, hybalance.eu

ACTIONS – DISTRIBUTED PTX

The following initiatives should be implemented to improve the business case of distributed PtX:

	Comments	Deliverables	Internal project owner	External collaboration partners
Assessing the possibilities of introducing more flexible electricity products/real-cost tariffs that ensure that the actual system value and costs in connection with the establishment and operation of specific plants is reflected in the costs of using the grid. This initiative is closely linked with and builds on the work of the existing tariff project.	Work on tariffs and flexible grid products is already ongoing, and these projects form the basis of better conditions for PtX. However, it is necessary to continue the studies on whether even more flexibility in both access to the grid and associated lower payment for using the grid is the best way overall to expand the market for PtX. This should be investigated for plants in the electricity transmission grid and for plants in the distribution grid, where many of these units will likely be connected.	Analyses of how business cases and barriers for PtX plants are affected by varying degrees of flexibility of grid access and grid costs. Analyses regarding the possibility of introducing more flexible products with associated flexible payment, also for customers in the DSO grids.	Electricity System Operator	Stakeholders, who are working actively with PtX plans, such as Ørsted, Mærsk, Nel and Copenhagen Airport, Evida and the distribution companies.
Maintaining the green value of the energy product and, for example, compliance with blending obligations under RED II to enable green hydrogen production used for transportation.	It will be important to the business case of many PtX projects that all hydrogen is 100% green and can be sold as a green product in all contexts. Today, this is only possible (according to RED II) with off-grid solutions.	The initiative is handled under *Green value.*	Group, Electricity System Operator, Gas TSO.	Stakeholders, who are working actively with PtX plans, such as Ørsted, Mærsk, Nel and Copenhagen Airport; The Danish Energy Agency and Danish Ministry of Climate, Energy and Utilities.
Energinet should work for a national carbon strategy with the aim of minimising the amount of carbon not used for the production of e-fuels, as the amount of available carbon will be a limiting parameter in the future.	Incentive schemes for PtX plants could be created to encourage the (re)use of carbon sources, which are otherwise difficult to use. Another powerful measure is to integrate biogas produced on straw in the subsidy schemes, which will increase available quantities of carbon significantly. In addition, the carbon strategy should naturally consider carbon storage (as a buffer between production/capture and consumption, CCUS) as well as permanent storage (CCS).	Initiate dialogue with the Danish Energy Agency about the need for and importance of a carbon strategy and the role it plays in realising Denmark's 70% CO2 reduction goal in 2030.	Group, possibly with contribution from Electricity System Operator	Stakeholders, who are working actively with PtX plans, such as Ørsted, Mærsk, Nel and Copenhagen Airport. The Danish Energy Agency and Danish Ministry of Climate, Energy and Utilities.

MAXIMISINGTHE VALUE OF HYDROGEN THROUGH GREEN CERTIFICATIONS

The value of hydrogen depends on its intended use. In addition to its use in the processing industry, three potential applications are currently emerging.

Firstly, hydrogen created with PtX can be used to decarbonise otherwise carbon-heavy sectors such as parts of industry and the heavy-duty transportation sector. A first step in sector coupling may be to establish a basis for the production of biofuels to fulfil the transport sector's blending obligations under RED II. To comply with blending obligations, a guarantee of origin or green certification is required.

Secondly, hydrogen and hydrogen production support the need for flexibility and storage in the electricity sector. This also includes a certain degree of sector coupling, as energy storage means increased levels of conversion to other forms of energy. And in relation to the political targets for CO2 reduction in the electricity and heating sectors and the national climate goals, green certification is an obvious value-creating measure.

Thirdly, in the short term, it is possible to export hydrogen to, for example, Germany which currently has a more extensive hydrogen market than Denmark. In the existing markets in other countries, green hydrogen is worth more than grey hydrogen (based on fossil fuels). In all cases of increased hydrogen production or PtX, the value of hydrogen is at its highest if a 100% renewable electricity origin is documented. Whether or not it is a matter of national climate budgets or the trading value of hydrogen outside Denmark, green certification of electricity will kick-start investments in PtX. It is therefore important that the Danish authorities prepare for a green certification system as part of the framework conditions for a future start-up of a hydrogen industry in Denmark.

The green value determines the commercial viability of all forms of RE-based PtX production. This is true irrespective of whether it is a PtX plant based in a landing zone, distributed PtX or hydrogen transported and stored in hydrogen infrastructure. In order to ensure stable and transparent framework conditions for market participants and potential investors in hydrogen production, it is therefore important to tackle questions about green certification or guarantees of origin upfront – in other words, now.

In the somewhat long term, a clarification of the role of hydrogen and biogas at a European level will be welcome, including whether there is a basis for an actual green market model.

ACTIONS – GREEN VALUE

Initiative	Comments	Deliverables	Internal project owners	External collaboration partners
Establish green certification for hydrogen or a guarantee of origin for the renewable electricity used to produce hydrogen via electrolysis.	Regardless of whether landing zones or distributed PtX solutions are established, there will be a need for energy transport. If the solution is hydrogen infrastructure via underground pipes, there is a need to address the question of certification of green hydrogen in the pipeline. In times of surplus renewable energy in the Danish electricity system, all hydrogen production is, of course, green; however, if electrolysers (for example due to process inertia) run in situations with less than 100% renewable energy in the electricity mix, a proportional certification can be made based on the current electricity declaration. In this context, interaction with the guarantee of origin is essential – not least to enable sector coupling, whereby green hydrogen is converted into other energy carriers and consumed as an end product. Documentation of the green value should have a digital foundation and take into account the physical properties of grids. In this way, the green value is realised and documented continuously and regularly.	Secure dialogue and progress with authorities and our owner's (The Ministry of Climate, Energy and Utilities) participation in international hydrogen agreements and collaboration.	Group, Electricity System operator, Gas TSO.	The Danish Energy Agency and the Danish Ministry of Climate, Energy and Utilities.
Clarification of European or international labelling rules are under development, and can be used to standardise certification for transportation fuels and blending obligations in accordance to RED II.	It could be important for the business cases of future PtX plants that all hydrogen is 100% green and can be applied for all purposes, which is only possible with off-grid solutions today. In the long term, all electricity produced in Denmark will be renewable, removing the need for green certification in favour of a 'made in Denmark' guarantee. Until then, different options are available, depending on the form of infrastructure developed. It may, for example, be more appropriate to declare the 'grey' hydrogen, if the majority of hydrogen in the Danish infrastructure is green. In relation to RED II, a proportional certification based on the current electricity declaration is insufficient, as it becomes uncertain how green the final product will be. This year, 64% of the last two years of electricity generation in Denmark is green, but does that make for 64% green hydrogen and 36% grey? If so, the business case for green hydrogen production will be undermined as there will be a 'forced' production of 36% low-value grey hydrogen, which may in turn cause economic losses for the producer. Or is it likely that some consumers use 100% green electricity, while others use 100% black?	Ensure that future standards and regulation concerning the green value of hydrogen is compatible or aligned with initiatives in our neighbouring countries and across Europe. As an example, the energy ministers of the Netherlands and Germany have made a joint declaration on North Sea hydrogen production and RED II.	Group, Electricity System Operator, Gas TSO.	The Danish Energy Agency and the Danish Ministry of Climate, Energy and Utilities and other energy policy circles

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