May 2023

Roadmap for a Danish hydrogen infrastructure for the future

Preface

The CIP Foundation presents with this report a roadmap for a coherent hydrogen infrastructure for Denmark.

The hydrogen infrastructure has been designed with a view to supporting the green transition in Europe and the politically set climate goals, boosting Danish exports and balancing the energy system.

The roadmap shows where the hydrogen pipe lines are most appropriately placed, how they are dimensioned, how they can best be connected abroad, and in what stages they can be expanded.

The war in Ukraine and the use of natural gas as a political weapon have brought Denmark and Europe into a historic energy crisis, which comes on top of an increasingly urgent climate crisis. Energy policy has become security policy, and this accentuates the need to increase the pace of the green transition.

In the past year, significant and far-reaching political decisions have been made regarding security of supply and the green transition. Decisions that change the conditions for our energy supply and the underlying infrastructure - and from a good starting point: prices for renewable energy have become competitive, and green energy can be harvested to an ever greater extent.

At the heart of the decisions is the need for electrification and the integration of green energy from volatile sources such as wind and solar together with new technologies to produce green hydrogen and PtX products that support the green conversion of energy-intensive industrial processes, heavy transport and agriculture.

However, the transition requires corresponding decisions about the infrastructure that will connect the new renewable energy with customers in Denmark and abroad as well as connect the new forms of energy. The infrastructure is crucial for security of supply and the commercial potential of green energy, whether we are talking about electricity or hydrogen, as it is the access to the market.

The urgent need for furthering the green transition is an opportunity for Danish companies and Danish society to reap great benefits by being "first movers". The CIP Foundation's Market Assessment from March 2023 showed that Denmark has some of the best prerequisites for producing green hydrogen in Northern Europe and becoming a major exporter on a scale corresponding to the current export of green energy and environmental technology. Green hydrogen can become the new oil and gas adventure - without climate impact and based on renewable sources.

However, this presupposes that timely, long-term planning of the collective infrastructure takes place from a central point of view, and that regulation and framework conditions are known and in place. It reduces the uncertainty and costs of developers and private investors and promotes the private investments in green energy and infrastructure, which will be decisive for the transition to succeed.

A relevant and well-dimensioned infrastructure will give Danish Power-to-X and hydrogen producers the opportunity to establish a strong market position early in a future European hydrogen market. A structured and coherent planning and robust expansion of the infrastructure across electricity, hydrogen and Power-to-X products will also be able to create a basis for an ecosystem of different players in the value chain and especially in the places in the country where large-scale projects are realistic. It will also be able to provide Danish companies with expertise that can be used globally and thus contribute to Denmark having an opportunity to maintain and expand its green technology export.

The CIP Foundation's roadmap for a coherent hydrogen infrastructure for Denmark must be seen in the context of the desire for security of supply, the potential for a green transition and CO2 reductions, as well as export and business development in Denmark.

We hope that the report is read in the light of the intention for which it was written.

Enjoy the read!

Anders Eldrup
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Summary

Denmark stands to gain a lot by investing in a hydrogen pipeline network with connections to neighbouring countries. The combination of favourable conditions for the production of renewable energy and green hydrogen and the potential for production far in excess of domestic demand constitutes the basis for green hydrogen exports to Denmark's neighbouring countries at a total value of EUR 13.5 billion a year. The one condition for realising this export potential is to establish a hydrogen pipeline infrastructure with pipelines to other countries; initially, this will provide access to the markets in Germany, the Netherlands and Belgium. This is set to be a far-in-to-sea-hydrogen-fairytale, primarily in the North Sea, and will require a total investment of EUR 17.5 billion over the next 15 to 20 years. This amount will cover the construction of two dedicated 15 GW hydrogen islands in the North Sea with hydrogen pipelines to neighbouring countries designed to handle the long-term quantities expected to be supplied to especially the German market.

GREEN HYDROGEN HOLDS HUGE POTENTIAL FOR THE GREEN TRANSITION

Green hydrogen produced from renewable energy will come to play a critical role in the green transition of the energy-intensive industries as well as large parts of agriculture and the transport sector where direct electrification is not an option. Without green fuels and ammonia produced from hydrogen using Power-to-X (PtX) technology, Denmark will not be able to meet the political decarbonisation targets. Green hydrogen has the potential to reduce global CO_2 emissions by 20% by 2050, according to McKinsey.

This is why there is huge interest in green hydrogen as a decarbonisation tool as reflected by the historically high number of hydrogen projects around the world. The interest is also heightened by notable political initiatives such as the US Inflation Reduction Act and the Green Deal Industrial Plan for Europe, which support the production of green hydrogen and PtX products.

Generating green hydrogen is more costly than generating fossil-based hydrogen. First and foremost the price of green hydrogen is linked to the price of renewable energy and secondly also to the price of electrolysis technology. Over time, these prices will see a decline. Together with demands for net-zero emissions, rising CO_2 quota prices, duties, etc., this will result in lower prices of the green alternative. The best and least costly transport option for hydrogen is pipelines, and hydrogen will be produced where the green energy is least costly, that is, where the sun is shining and the wind is blowing.

DENMARK'S UNIQUE COMPETITIVE ADVANTAGE GENERATES HUGE EXPORT POTENTIAL

In Denmark, the conditions for producing renewable energy at competitive prices are good, especially in the North Sea and the Baltic Sea, thanks to the country's large areas offering a combination of good wind conditions and shallow waters which are ideal for the establishment of offshore wind farms and energy islands. This provides Denmark with a cost advantage of up to 10% in large-scale hydrogen production based on energy islands and dedicated hydrogen hubs with international pipelines, as discussed in the market assessment produced by the CIP Foundation.

Since Denmark is moreover set to become self-sufficient in green energy, this provides the basis for large-scale exports to the country's neighbouring countries, some of which have a declared strategy to import green hydrogen for the transition of energy-intensive sectors where electrification is not possible. This applies especially to Germany, the Netherlands and Belgium, but Poland and parts of Sweden may also need to import hydrogen.

From a long-term perspective – and by exploiting the currently known and screened areas for renewable energy – Denmark will be able to produce 216 TWh of green hydrogen a year, when the electricity needed for the direct electrification of Denmark is accounted for.

This goes far beyond Denmark's domestic demand. As a result, almost 200 TWh of green hydrogen can be exported at an annual value in the vicinity of EUR 13.5 billion (fixed prices). This is slightly more than the country's total exports of green energy and environmental technology. And more than the country's annual net exports of oil and gas over the years so far. Contrary to oil and gas extraction, green hydrogen is based on a non-depletable source.

A HYDROGEN PIPELINE INFRASTRUCTURE – THE GATEWAY TO THE MARKET

Connecting producers and consumers requires a hydrogen pipeline infrastructure. This will provide access to the market. Considering the huge export potential, it is paramount that the hydrogen infrastructure is developed in parallel with and connected to other countries' planned infrastructure in the North Sea, the Baltic Sea and from an onshore facility to Germany. This will provide access to the most important consumers while at the same time generating economies of scale with multiple parties sharing the costs. In the light of this, the Danish government authorities and planners must ensure that joint efforts are made in cooperation with the country's neighbours – especially Germany, the Netherlands and Belgium – which are the main markets that Denmark is expected to cater for. Also, a common understanding of the need for transporting hydrogen and with this also the dimensioning of the hydrogen pipelines should be reached.

CORRECT DIMENSIONS FROM THE OUTSET

Although it takes time to expand the required renewable energy and hydrogen production, the dimensions of the infrastructure must be able to handle the future quantities. As a focal point, the hydrogen infrastructure must be given sufficient dimensions from the outset to be able to handle the quantities expected for the future. Preferably the pipes should be large right from the start since the installation costs are of a magnitude where it will pay off to use somewhat overly large but more expensive pipes from the outset rather than having to install parallel, smaller pipes in several stages.

Using larger pipes would also provide added flexibility as regards the storage of hydrogen in the pipes whereas smaller pipes would have to be pressurised and expanded with compressor stations at an early stage.

By designing the infrastructure for the future demand, the need to store hydrogen in underground caverns would also be limited during the first period while the market is being developed.

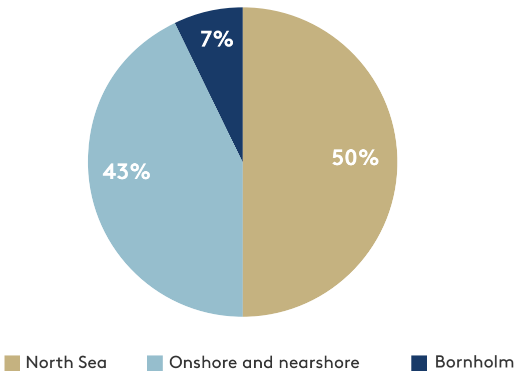
DIFFERENCES BETWEEN HYDROGEN PRODUCED ONSHORE AND ON OFFSHORE ENERGY ISLANDS

As discussed in the market assessment published by the CIP Foundation in March 2023, the major consumers of Danish hydrogen are expected to be especially Germany, the Netherlands and Belgium with an overall import requirement of up to 500 TWh. The potential for production of green hydrogen in Denmark is very much linked to the wind resources – especially those far from the shore and mostly in the North Sea.

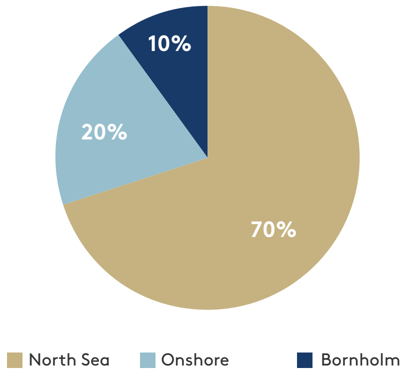
Several advantages are found in terms of costs and economies of scale when producing hydrogen close to renewable energy sources, and there is also the question of scale when producing hydrogen at sea on energy islands, in fact more likely hydrogen islands, where especially hydrogen will be produced in addition to green electricity.

According to forecasts, a large share of the future green hydrogen production can be provided by two dedicated hydrogen islands in the North Sea, at Dogger Bank and in the

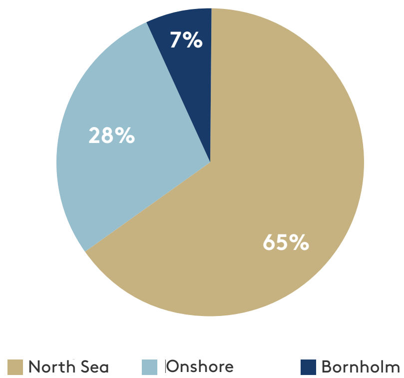
Breakdown of renewable energy potential ≈ 104,6 GW



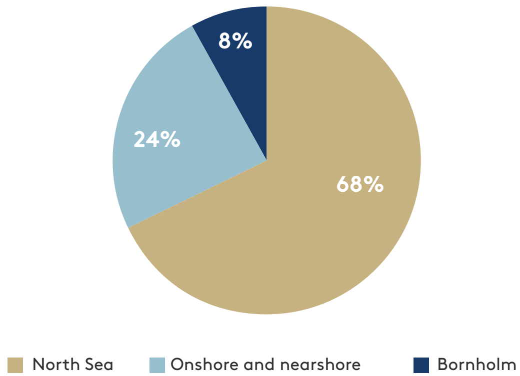
Breakdown of expected hydrogen export ≈ 197 TWh ≈ 13,500 million EUR

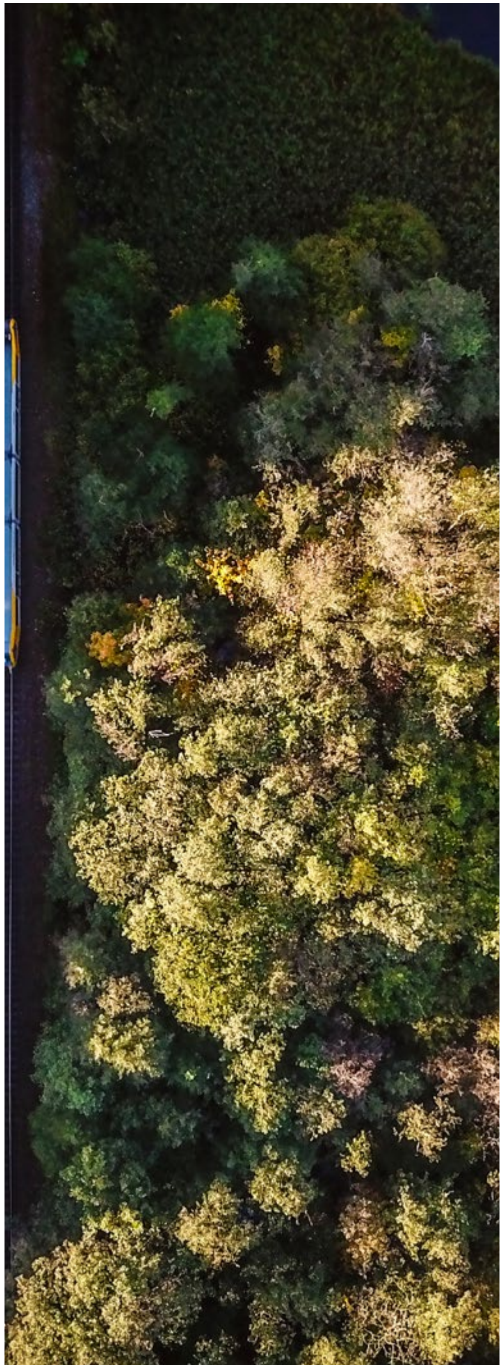


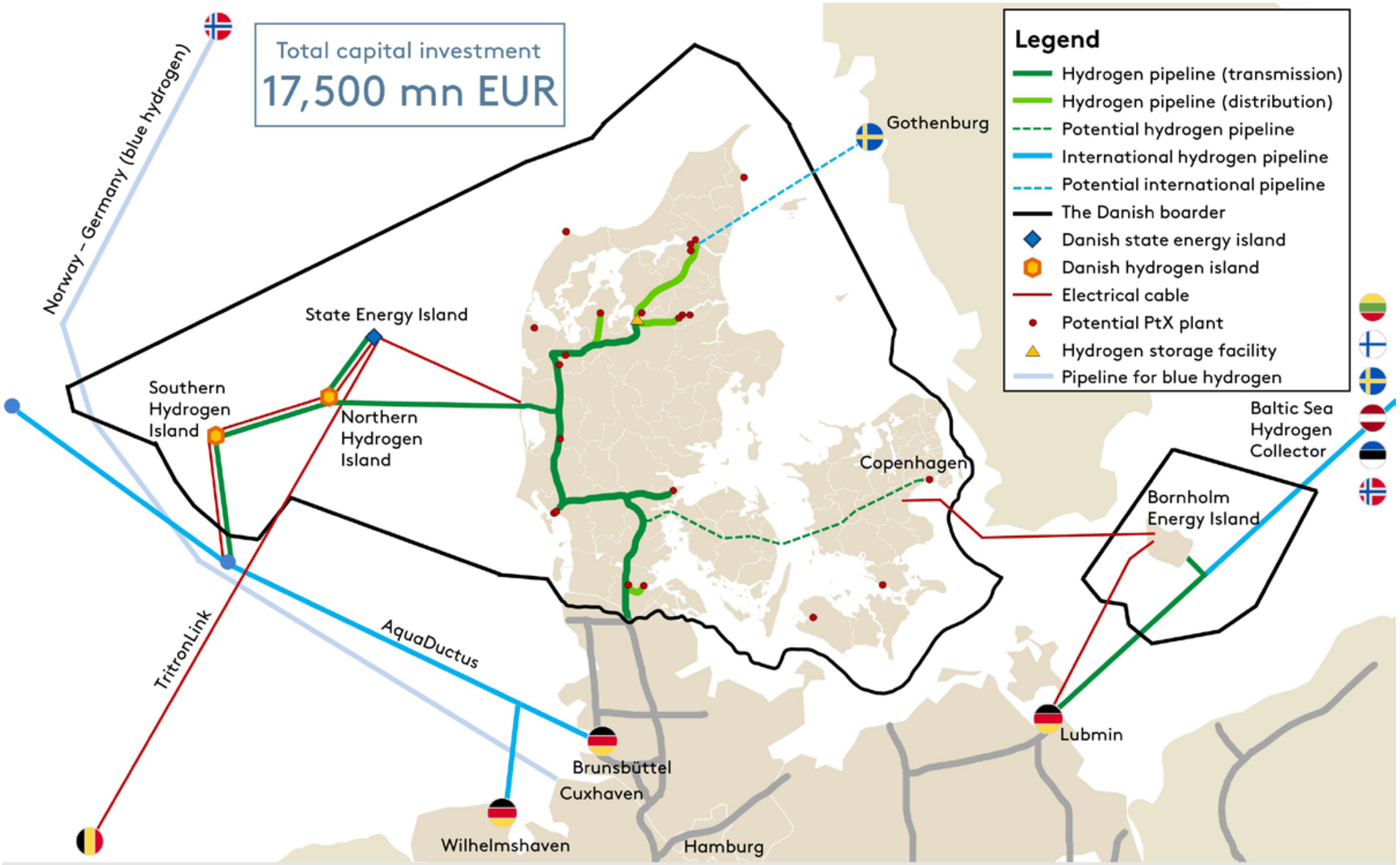
Expected hydrogen production based on infrastructure in total ≈ 216 TWh



Breakdown of investment need ≈ 17,500 million EUR







The CIP Foundation's plan for a coherent hydrogen infrastructure
Fully completed by 2045

vicinity of the planned, future Danish state-owned energy island with pipelines to Denmark as well as to Germany. To this should be added the production at the Bornholm Energy Island where there will be an advantage in linking that to an international pipeline.

However, hydrogen production far into the sea on dedicated hydrogen islands is a much more complex and risky investment and with fewer and larger players than onshore hydrogen production. As regards the onshore hydrogen production and its infrastructure, the discussion is based on the market dialogue conducted by the Danish TSO Energinet and the Danish gas distributor Evida in 2022 which resulted in reports of 70 hydrogen producing facilities and an overall production of 37 TWh. According to a screening from KPMG, two-thirds of the quantities from these projects are found to be realistic and will need to be linked to a hydrogen infrastructure.

The layout of the hydrogen infrastructure is built on these facilities and their locations, the accessibility of renewable energy in the area and the structure, capacity and plans for expansion of the electricity grid. Another factor has been the potential consumption by major cities or industry clusters of excess heat from hydrogen and PtX facilities. This points to a need in especially the western part of Denmark (Jutland) based on a pipeline from Germany through the peninsula to its northern part (Northern Jutland) with distribution lines to key hydrogen producers in the western and northern parts of Jutland.

HYDROGEN LENDS FLEXIBILITY TO THE ENERGY SUPPLY AND IS NECESSARY TO MEET POLITICAL TARGETS

In the design of the hydrogen infrastructure another important aspect has been to take the flexibility of the overall energy supply into consideration so as to benefit from the advantages of the connection to sectors and to balance the various energy sources. Contrary to electricity, large scale storage of green hydrogen is possible and the hydrogen production can be scaled up or down according to the quantity of renewable energy in the system.

Consequently, the hydrogen production can contribute to balancing the electricity grid and reducing the need to expand the electricity grid to be able to handle the future large quantities of renewable energy, which is the political ambition.

In fact, it is not easy to imagine that the electricity grid, not only in Denmark but also in other countries, will be able to absorb the large quantities of green electricity which are in store according to the political declarations for the North Sea and the Baltic Sea. In the light of this, hydrogen is an indispensable tool to meet the political targets. And for this reason, exports are in fact a necessary step since the targets exceed Denmark's own consumption by far.

A QUESTION OF SECURITY WITH MULTIPLE PIPELINES

The geopolitical developments have made it imperative to take the security of the infrastructure into consideration. One aspect of this is to lower the vulnerability and the risk of bottlenecks by ensuring flexibility through the installation of multiple pipelines and also by switching between electricity and hydrogen production.

Accordingly, the need for power cables and reinforcement is also incorporated into the infrastructure plan. And with pipelines to both Denmark and Germany for electricity and hydrogen there is ample opportunity to optimise the transport of energy. Meanwhile this also ensures that the electrolysis facilities on the hydrogen islands do not become bottlenecks when renewable energy is to be sold from the nearby wind farms and that the production can switch between hydrogen and electricity when warranted by market prices.

Although a single pipeline from the large production sites might basically have been sufficient, the issue of security and also flexibility in relation to the market also calls for several channels.

STAGED EXPANSION OF HYDROGEN INFRASTRUCTURE

Since hydrogen production is dependent on the quantity of renewable energy produced and when this is realised, it makes good sense to time the installation of the hydrogen infrastructure accordingly. Consequently, the first proposed step is to start by installing the onshore hydrogen infrastructure thereby making it possible to supply hydrogen to Germany and then gradually expand by offshore pipelines and multiple channels. This would also provide flexibility and the opportunity to learn more about the specific needs stage by stage over time.

Although the establishment of a backbone hydrogen infrastructure in the western part of Denmark is the first stage of the expansion plan, setting up an offshore infrastructure in the North Sea with a view to exports is the key and pivotal element of the overall plan. Potentially, the dimensions of the expected, state-owned energy island are insufficient to provide sufficient capacity for a production of electricity for the direct electrification of Denmark and Belgium with sufficient energy left for profitable hydrogen production with a relevant infrastructure. In this context it is also worth noting that the intention is to build the energy island at the best site in the North Sea in terms of wind and seabed conditions.

Thanks to the structure of the expansion plan, each of the stages can be realised individually and independently of future decisions. This provides for a reliable and solid socioeconomic investment case. As an example, the volume of green hydrogen to be transported across Denmark remains uncertain.

Consequently, the need for the connection can be qualified over time and included at a later stage. In parallel with this, a potential regional need for green hydrogen is starting to emerge around Gothenburg in Sweden, a region that Denmark could potentially be connected to. In view of this, these hydrogen pipelines are not part of the expansion plan but could be included if future analyses point to a relevant need.

In order to realise the outlined expansion plan, a number of central decisions have to be made at central level within a short time span for the sake of, for example, the developers and contractors who are to build the infrastructure. At the general level, it is imperative that decisions are made concerning the public calls for tender for the offshore wind and the open-door projects to ensure sufficient renewable energy both for the electrification process and for the hydrogen production. The central decisions to be made are discussed below in relation to the expected process involved in establishing the hydrogen infrastructure projects.

TOTAL INVESTMENT REQUIREMENT OF DKK 130 BILLION DKK

The investment requirement is determined using the capital investments that are directly linked to the recommended infrastructure, that is, hydrogen pipes, compressors, hydrogen islands and the known resulting need for

Investments	Capital investments, mn EUR	Operating costs, mn EUR per year
Phase 1: 2024-2018 The land-based backbone	3,500	80
Phase 2: 2029-2035 Offshore pipeline and export	5,000	120
Phase 3: 2036-2045 Upscaling, multiple pipelines, and balancing	9,000	190
Total	**17,500**	**390**

Source: COWI (2023)

reinforcement of the electricity infrastructure. The costs of facilities that have already been decided are not included, such as the state-owned energy islands in the North Sea and on the island of Bornholm.

Nor do the hydrogen infrastructure investments include investments for expansion of the renewable energy and electrolysis since these investments are linked to the production side. Here the development of the market and the technological development will push prices downwards. To this should be added the implications of the new possibiliy of over-plantning (closer positioning of offshore wind turbines). The budgeted investment totals about EUR 17.5 billion over a 20-year period and most of the investment is due around 2030-2040. This will make the hydrogen infrastructure the largest capital investment in the history of Denmark.

By comparison, the investment budgeted for the Femern Belt is EUR 7.3 billion (2015 prices). Each of the phases of the hydrogen infrastructure expansion process can also be compared with the costs of expanding the electricity grid where, for example, the Danish TSO Energinet expects to invest EUR 3.3 billion in the transmission of electricity in 2022-2027.

RISKS OF ESTABLISHING A HYDROGEN INFRASTRUCTURE

The establishment of an infrastructure of this magnitude and with a time horizon of this scale holds certain risks. First and foremost, there is the uncertainty of the market's future needs and with this the dimentions of the infrastructure. Part of this risk can be reduced through political decisions on decarbonisation and support of hydrogen production.

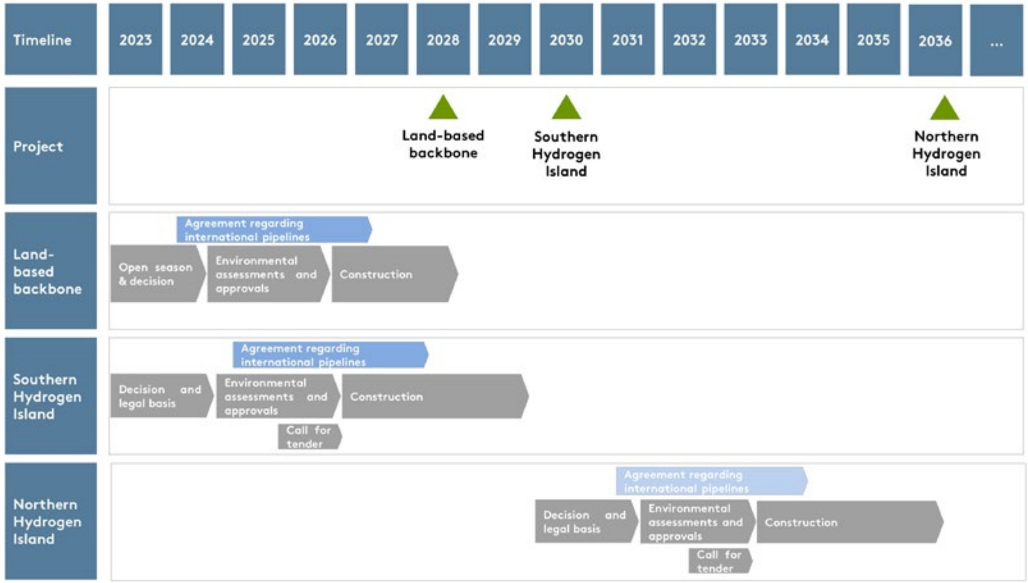
In addition, the market players can be bound by their views on the future needs through 'open season' reporting. According to experience from other markets, the supply creates its own demand. Consequently, no action also poses a risk. A laid-back approach will leave the initiative to others to decide where the future energy hubs will be located in Europe and who will produce the green energy of the future.

Besides, there are also technological risks that could go both ways. As an example, the International Energy Agency (IEA) estimates that the price of electrolysis will drop to 70% of today's level by 2030, which would make green hydrogen more competitive. Conversely, competition might develop from alternatives such as battery storage and fuel cells – areas which are seeing massive technological development. There are not many alternatives to hydrogen, however, when it comes to energy-intensive industrial processes and heavy transport, and this puts a floor under the market.

The largest risks are linked to the resources. They concern qualified personnel for the green transition, which already now presents a challenge. They concern raw materials and rare metals that are only found in a few places and through strained supply chains. They concern the resulting infrastructure need in the form of port capacity. And they concern funding since green capital seems to be available, but the challenge is to channel it to the specific projects through funding models of relevance to the private players.

Add to this the challenge that many countries have set their own climate targets and have projects to be realised almost at the same time, which results in bottlenecks. This can be managed partially by means of strict time schedules and efficient coordination and planning across borders and sectors.

Central decisions and establishment



THE ROLE OF THE STATE AND THE NEED FOR REGULATION

The market for green hydrogen is still not mature and needs a framework that can help reduce risks for future market players. It is also characterised by the classic 'the chicken or the egg' dilemma since decisions have to be made concerning large, capital heavy and irreversible investments at an early stage considering the development of the market.

The Danish State can play an active role when it comes to reducing the risks involved in establishing the hydrogen infrastructure. First and foremost by assuming a risk regarding the future use of the common hydrogen infrastructure which will be paid back over time.

Next, by putting in place a relatively flexible and uncomplicated framework from the outset to allow for the fact that this is a market which is in the development phase while at the same time accommodating the market's need for knowledge of the long-term framework conditions. A sort of 'playground regulation' for a period of time which can later take the form of concrete rules and regulations. In principle, this is also the type of regulation of the hydrogen market which has been outlined by the European Union.

Finally, the State also plays a significant role by having appointed the central planning authority and coordinator and supporting transparent and more predictable approval procedures, for example through binding deadlines for procedures and/or parallel processes by the various regulatory authorities. Critical to Denmark's future role in hydrogen production is also time and the speed of making decisions. And with this also how much support Denmark can lend to Europe in terms of energy and security and which climate reductions Denmark can support.

The CIP Foundation's recommendations for a hydrogen infrastructure

Denmark is in a unique position to support large CO2-reductions in Northern Europe as green hydrogen can take the place of fossil fuels. The climate effect of using green hydrogen instead of hydrogen from natural gas corresponds to one-tenth of Germany's total emissions and 1.5 times Denmark's current own emissions. And if green hydrogen were to replace oil and coal, the potential would be even bigger.

1. For these reasons, Denmark should establish green hydrogen production and **invest in a coherent hydrogen infrastructure.**

Green hydrogen can become Denmark's next export adventure worth up to EUR 13.5 billion a year with the country exporting most of the hydrogen it produces – especially in the North Sea which is a key spot for renewable energy in Northern Europe.

2. For these reasons, Denmark must – as part of the expansion process – focus on **pipelines to neighbouring countries** and offshore pipelines and step up the cooperation with international infrastructure operators.

A hydrogen infrastructure requires large and irreversible capital investments and has to be in place long before the market is fully mature.

3. For these reasons, Denmark must **design the pipelines big enough for the needs of the future.**

Green hydrogen is still in its early infancy where many of the future market players still remain to see the light of day and where individual projects are characterised by considerable uncertainty.

4. For these reasons, Denmark needs a **flexible framework from the outset** and supportive conditions where the State assumes some of the risk by supporting a common hydrogen infrastructure with a long pay-back period.

All in all, the CIP Foundation proposes to build a coherent hydrogen infrastructure for Denmark that can support the political targets and the potential for expanding the production of renewable energy and link green hydrogen from Denmark to the consumer markets.

5. For these reasons, the coherent hydrogen infrastructure will become **Denmark's largest capital investment** spanning two decades and amount to EUR 17.5 billion and with hydrogen pipelines extending more than 1,300 km.

The demand for green hydrogen by our closest neighbours will exceed by far what Denmark will be capable of producing, which lowers the risk. However, risks can also be lowered in other ways.

6. For these reasons, **the development of the hydrogen infrastructure must be a staged process** that is capable of standing alone and is independent of future decisions (no-regret decisions). The more uncertain part of the development must be qualified in tandem with the market development..

The time from making the decisions until a ready-to-use hydrogen infrastructure is in place is long. For offshore wind farms, the period from decision to operation is about nine years. Time is not unlimited for the climate.

7. For these reasons, **we must start making the decisions** for the future interconnections and structuring approval processes etc. so as not to waste time unnecessarily on procedures.

Our generation has the choice to decide whether Denmark is to continue to be the green pioneer of the future. And it is our choice whether Denmark is to use its natural resources and good conditions for producing large quantities of renewable energy to support the need of other countries in the green transition.

The renewable energy can either be exported as is or be used as a green 'keystone' which is in effect the role that green hydrogen can play by tying energy types together and thereby support the green transition of the most challenging sectors.

With ability comes responsibility… this also relates to the climate.

CIP fonden

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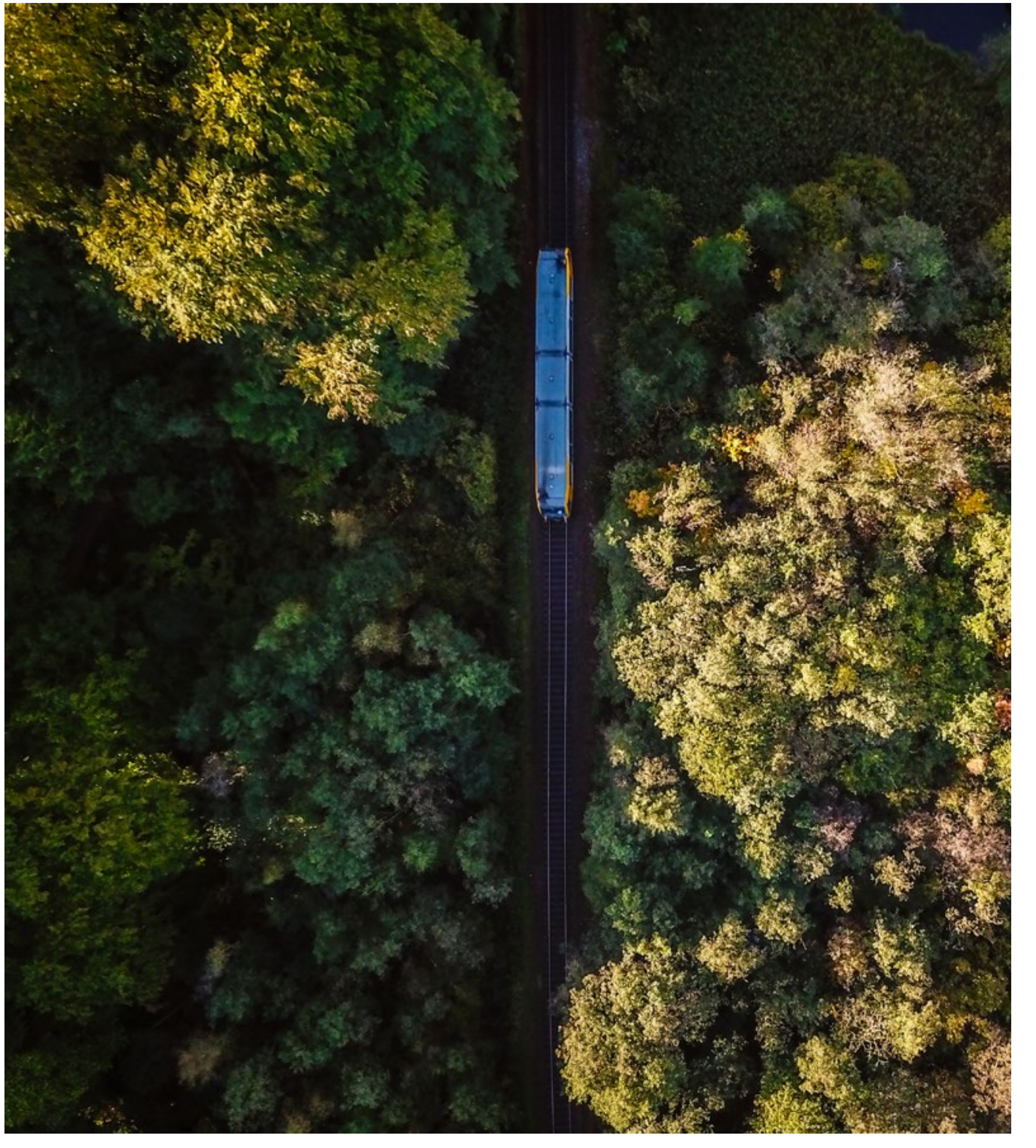


At the CIP Foundation we conceive and implement long-term projects that support the transformation of Danish society towards a more sustainable future. We are an independent and non-profit organisation that delivers tangible and implementable solutions for a long-term transformation of Danish society.

For more information, visit cipfonden.dk

Why do we need a hydrogen infrastructure?

Chapter 1

Green hydrogen and Power-to-X (PtX) products can replace fossil energy in a range of sectors where the transition process is otherwise difficult, for example the energy-intensive industry and part of the transport sector. Consequently, green hydrogen plays an important role when it comes to the development of new green business and export opportunities in Denmark. Since hydrogen is transported least costly in a hydrogen pipeline infrastructure, the establishment of such an infrastructure is a condition for setting up the production of hydrogen and derived PtX products in Denmark.

Transporting hydrogen and PtX

The best and cheapest way to transport hydrogen is through a hydrogen pipeline infrastructure. This can be dedicated hydrogen pipelines or retrofitted natural gas pipelines. Contrary to hydrogen, long distance transport of PtX products is easier and less costly by sea.

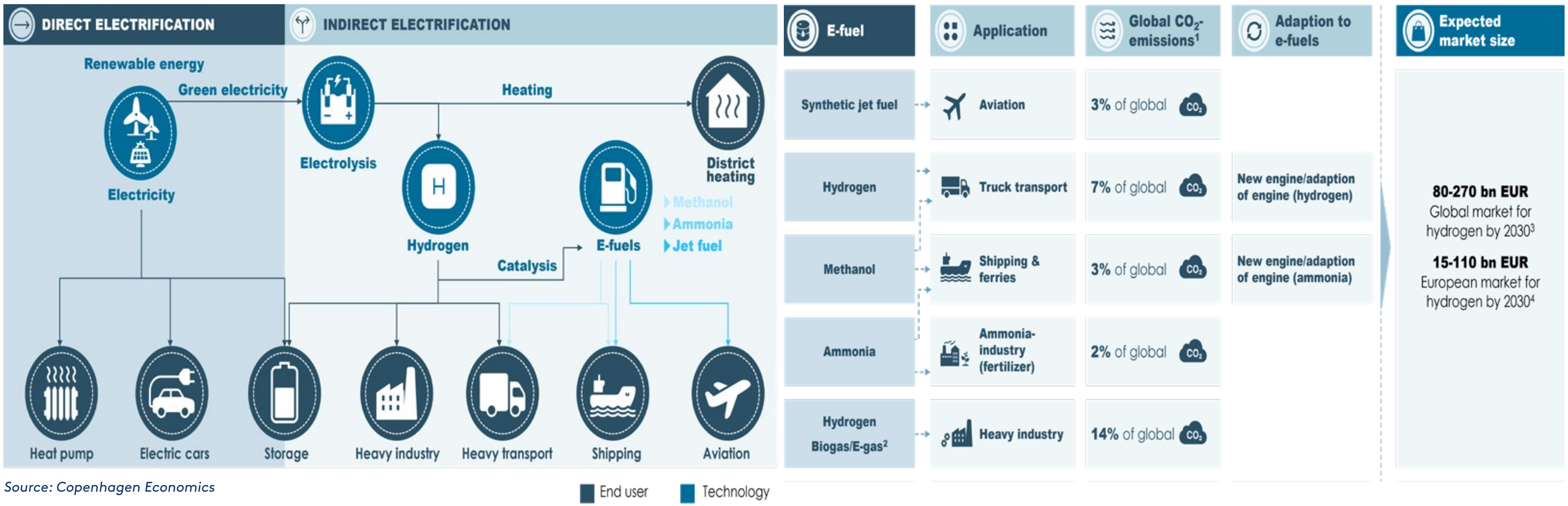
Source: The CIP Foundation (2023), Brinckmann (2023)

1.1 Hydrogen will become a key component in the future energy system

phase-out of fossil fuels, such as coal, oil and natural gas, calls for green alternatives. While passenger transport, household heating and some industrial processes can be electrified, electrification is not an option for neither the energy-intensive industry, sea transport nor air transport. Their requirements will have to be covered by green fuels with a high energy content and for this purpose green hydrogen will come to play a key role.

Green hydrogen is the result of electrolysis – a process in which green electricity from wind turbines or solar panels, as examples, is used to split water. The resulting hydrogen can be used immediately to replace coal in the energy-intensive industry or petrol for energy-intensive road transport, or it can be further refined into PtX fuels, such as green methanol, to replace fossil-based aviation fuel or green ammonia to be used for sea transport and by agriculture. Figure 1.1 illustrates the significance of green hydrogen for the energy system of the future.

Figure 1.1: *Green hydrogen as part of the overall energy system*



Source: Copenhagen Economics

GREEN HYDROGEN IMPROVES RELIABILITY OF SUPPLY

In addition to its key role in the transition process for sectors whose transition is difficult, hydrogen will also play a major role in the energy system as such. The expansion of the renewable energy production based on volatile sources, such as wind and solar energy, adds to the pressure on the energy system which is currently unable to store the energy until it is needed. Here hydrogen – jointly with biomass – will play a key role as an energy storage option which can be filled at times when the energy requirement for direct electrification is low and be consumed as required. As a result of this, it is possible to increase the production of green hydrogen when there is a surplus of renewable energy and with this relieve the pressure on the electricity grid. This will improve the reliability of supply as fossil fuels are phased out.

1.2. The market for green hydrogen is being developed

Whereas a market for grey (fossil-based) hydrogen already exists with an appropriate infrastructure in countries such as Germany, the Netherlands and Belgium and also the USA, the market for green hydrogen is in its infancy. According to Topsoe's estimate, the current global electrolysis capacity corresponds to 3.5 GW renewable energy in total. The development of the market points towards a marked capacity build-up going forward. Denmark aims to achieve an electrolysis capacity of 4-6 GW by 2030.

Green hydrogen is not yet a commercially available product with a price. The market will be expanded as the green transition accelerates the need for a green energy carrier capable of servicing the energy-intensive industries and forms of transport where electrification is not an immediate option.

The market for green hydrogen is already supported by several political measures and market-related initiatives, which either reduce the costs of producing green hydrogen or increase the price of fossil alternatives with the effect that the 'green bonus' is less pronounced.

Among these initiatives are political goals to achieve decarbonisation and climate neutrality, sector demands to achieve climate reductions, specific requirements to mix fuels with green fuels, a CO2 tax to be imposed on businesses (in Denmark), an EU requirement to report on climate impact, and a range of financial incentives offered through support programmes, low taxation and indirect subsidies such a reduced tariffs.

Examples of market-related initiatives are CO2 quota prices increasing over time, company-specific climate targets based on the company's own ESG targets, the price of green electricity and the technological progress resulting in more efficient electrolysis and allowing large-scale production. The sum of these aspects means that during the next few years a considerable market of a regional nature will develop for green hydrogen and for starters with geographical limits on the competition[1].

THE FIRST STEPS TOWARDS A HYDROGEN PIPELINE INFRASTRUCTURE

With an energy-intensive industry of considerable proportions, the current import ban on Russian gas and ambitious climate targets, Germany is facing the enormous challenge of getting access to sufficient quantities of green fuels to replace coal, oil and natural gas. As a result of this situation, Germany is looking towards other countries, including Denmark, to gain access to sufficient quantities of green hydrogen. The first major step towards a Danish hydrogen economy was taken when Denmark and Germany in March 2023 signed a Declaration of Intent to link the two countries with a hydrogen pipeline so that in future Danish surplus energy can be used for the transition of the energy-intensive industry in Germany.

Although a hydrogen pipeline to Germany is important for the new hydrogen industry in Denmark, this pipeline only constitutes a small fraction of the solution. In Denmark, a large number of hydrogen projects are in the pipeline, so to speak, and since hydrogen should be carried through a pipeline infrastructure, a far more extensive onshore hydrogen infrastructure is required to link Danish producers of hydrogen with the interconnection to Germany. To this should be added Denmark's large potential in the North Sea where the potential for Danish energy production will multiply the country's current production. To exploit this potential, a hydrogen infrastructure will also have to be expanded into the North Sea.

1.3. Today's hydrogen market

The international activity related to hydrogen is a testament to a rapidly developing market. Large parts of the world have set themselves ambitious climate targets, and green hydrogen has the potential to reduce global CO2 emissions by one fifth by 2050. This results in an increasing need for hydrogen in the energy-intensive industries and parts of the transport sector where electrification is not an immediate option.

1 This is supported by the circumstance that even today the price of grey hydrogen differs considerably across countries and regions, according to Axcelfuture (2023)

As already mentioned, Europe already uses fossil hydrogen to some extent, mainly the steel industry and for the production of ammonia and petrochemical products.

Today, the overall European consumption of fossil hydrogen totals about 350 TWh. Germany, the Netherlands and Belgium are among the largest consumers, and their combined consumption is equivalent to more than one third of Europe's overall consumption[2]. Although Germany is the largest producer of fossil hydrogen in Europe today, neither Germany nor the two other countries expect to be able to meet their own growing need for green hydrogen in future. The interest in green hydrogen as a decarbonisation tool is large as reflected by the historically high number of hydrogen project worldwide[3].

GERMANY, THE NETHERLANDS AND BELGIUM ARE EXPECTED TO CONSUME LARGE QUANTITIES OF GREEN HYDROGEN

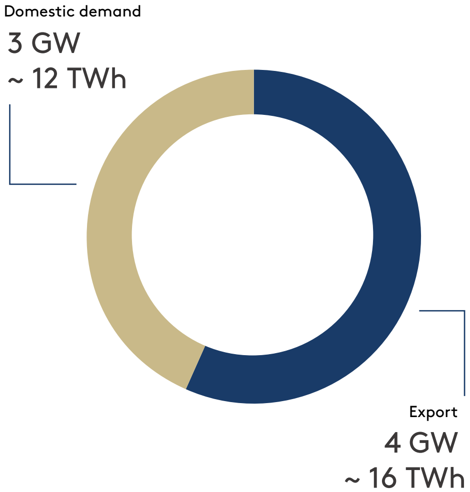
By 2030, these three countries expect their hydrogen consumption to be about 215 TWh and by 2050, when the climate neutrality target must be met, the consumption is assumed to reach at least 500 TWh. Figure 1.2 shows the development of the envisaged hydrogen demand of the three countries. Despite a strong demand for hydrogen, these countries do not expect to be able to produce the required quantities themselves. According to the national hydrogen strategies of the three countries, they have all declared themselves dedicated import nations. This is reflected in their international activities where they enter into contracts with suppliers of green fuels around the world, including Denmark.

By 2030, when according to forecasts the overall demand of the three countries will be about 215 TWh, they only expect to be able to produce enough green hydrogen to cover between 15 and 20% of their demand[4]. This generates a need to import more than 170 TWh, corresponding to a value of more than EUR 10.7 billion a year.

DENMARK SOON TO BE SELF-SUFFICIENT IN GREEN ENERGY

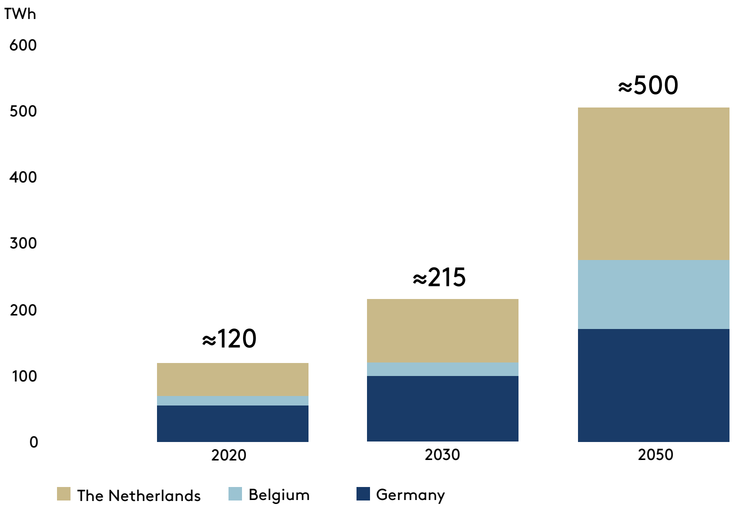
Contrary to Germany, the Netherlands and Belgium, Denmark's need for energy is low. According to the Danish Energy Agency, Denmark will be self-sufficient in green electricity as early as 2027, and the country will be self-sufficient in hydrogen before 2030. After 2030, Denmark's energy production is expected to grow considerably faster than the consumption of energy, as can be seen from Figure 1.3. This opens up the gateway for Denmark to become an exporter of green energy, including hydrogen, which is in demand by much of Europe. According to the Danish En-

Figure 1.3: *According to forecasts, Denmark will produce more than twice the quantity required to cover the domestic need for hydrogen by 2030*



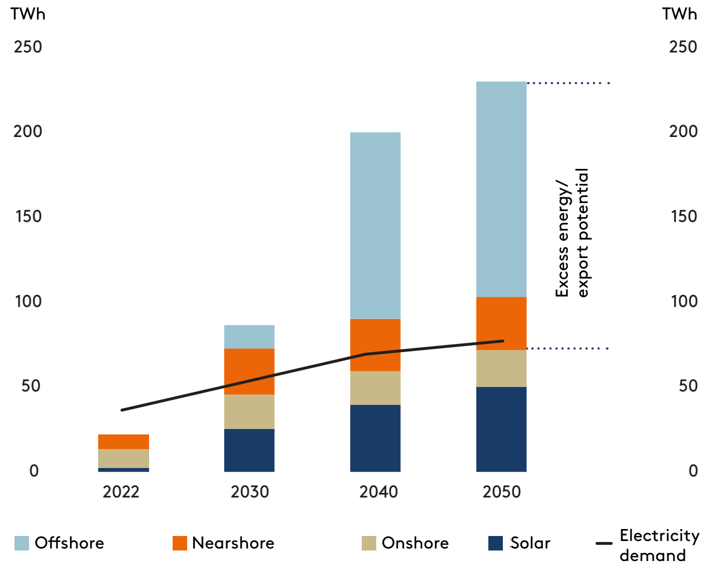
Source: Own calculations based on figures from the Danish Energy Agency (2023) and the Danish Government's climate partnership for energy and supply (2020)

Figure 1.2: *Hydrogen demand from Germany, the Netherlands and Belgium from 2020 to 2050 (TWh)*



Source: Market Assessment, the CIP Foundation (2023)

Figure 1.4: *Energy production and consumption forecast for Denmark (TWh)*



Source: The Danish Energy Agency (2023)
Note: Denmark's energy production from various sources and power consumption is stated in TWh.

2 The CIP Foundation, 2023. Europe's overall consumption totals 341 TWh, and the consumption of Germany, the Netherlands and Belgium totals about 120 TWh.
3 McKinsey (2023)
4 Own calculations based on the CIP Foundation (2023)

ergy Agency's forecast, Denmark will exceed the political targets as early as 2030 with hydrogen production of 28 TWh. More than half of this, 16 TWh valued at about EUR 1 billion, can be exported[5].

1.4 Many onshore hydrogen projects in the pipeline

During the period up to 2030, the Danish production of green hydrogen will most likely be generated by a number of onshore hydrogen and PtX projects, either linked to nearshore wind or onshore wind and solar energy. A market dialogue, carried out by Danish TSO Energinet and gas distributor Evida, shows that the number of projects rose from 32 to 70 from 2021 to 2022[6].

The latest market dialogue from 2022 indicates a future hydrogen production that exceeds both the political targets and the forecasts made by the Danish Energy Agency. Based on a range of evaluation criteria, an analysis of the probability that the projects announced will be realised estimates that most of the forecast production, equivalent to about 37 TWh, is expected to be realised[7].

The onshore hydrogen and PtX projects in Denmark will most likely be located close to renewable energy resources, the existing electric infrastructure, the district heating network and other activities in the value chain. As a result of this the projects are assumed to be widespread in terms of geography, as can be seen from Figure1.5.[8] Precisely the geographic spread highlights the need for a more comprehensive hydrogen infrastructure to enable the hydrogen producers to deliver to the network and the PtX producers to access hydrogen. This is also evident from the 2022 market dialogue which concludes that practically 90% of the hydrogen produced by hydrogen-only producing projects will most likely be transported via a pipeline hydrogen infrastructure.

Conversely, also dedicated PtX projects exist with an own supply of renewable energy with the result that they need not be connected to a pipeline hydrogen infrastructure. Hydrogen projects corresponding to more than half of the expected production find that a hydrogen infrastructure is imperative for their realisation[9].

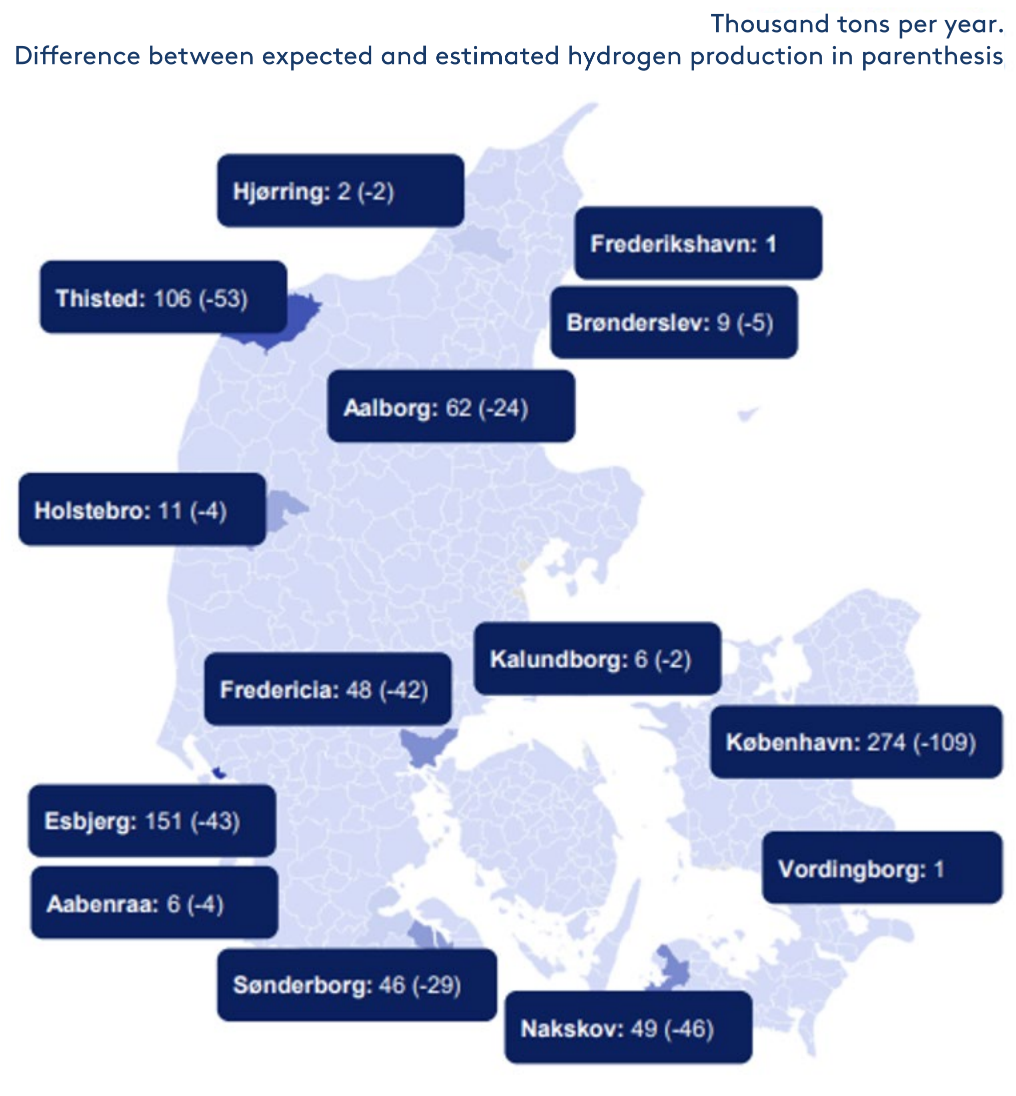
Although the recently concluded Declaration of Intent about a hydrogen pipeline from Germany to Denmark is an important step towards linking a future supply in Denmark with the demand from Germany, a more comprehensive domestic infrastructure is required in Denmark if today's projects on the drawing board are to be able to deliver to the German market.

According to forecasts, more than 60% of the upcoming projects will be exporting their production, and confidence in the existence of a future hydrogen infrastructure in Denmark is decisive for their willingness to invest and thereby the realisation of the projects.

1.5. The hydrogen production potential is especially found offshore

The onshore hydrogen and PtX projects in Denmark hold great potential. However, Denmark's biggest opportunities lie at sea. By 2030, Denmark's onshore production will total

***Figure 1.5:** Estimated realised hydrogen production by municipalities in Denmark*



Note: Figure 1.5 shows the actual hydrogen production forecast for 2030. The figures in brackets show the production quantity deducted following an analysis of the likelihood of project realisation.
Source: KPGM for the CIP Foundation, 2023

5 The CIP Foundation (2023) based on the Danish Energy Agency (2023)
6 KPMG (2022)
7 Own calculations and KPMG (2023). 1 GW electrolysis capacity is assumed to result in annual production of 4 TWh
8 KPMG (2023)
9 KPMG (2022)

less than 10% of the overall demand from Germany, the Netherlands and Belgium. If Denmark is to make a contribution to the European green transition process, large-scale offshore hydrogen production is required.

Denmark's early stage self-sufficiency will pave the way for the potential to exploit the country's large sea territory to produce hydrogen with the intention to export. Offshore hydrogen production will generate some significant economies of scale of between 15% and 20%[10] compared with onshore production.

A condition for this is that the energy is produced and converted into hydrogen locally – for example at dedicated hydrogen islands. Hydrogen islands in the North Sea will provide Denmark with a unique opportunity to export low-cost green energy to its neighbouring countries to the benefit of both the green transition and the Danish economy.

Denmark's attractive offshore sites characterised by good wind conditions and shallow waters are found especially in the North Sea. Consequently, among the North Sea nations, Denmark will be able to produce green energy at the lowest cost. Compared with Germany, Denmark will be able to produce hydrogen more cost effectively, equivalent to a cost difference of between 5% and 10%[11].

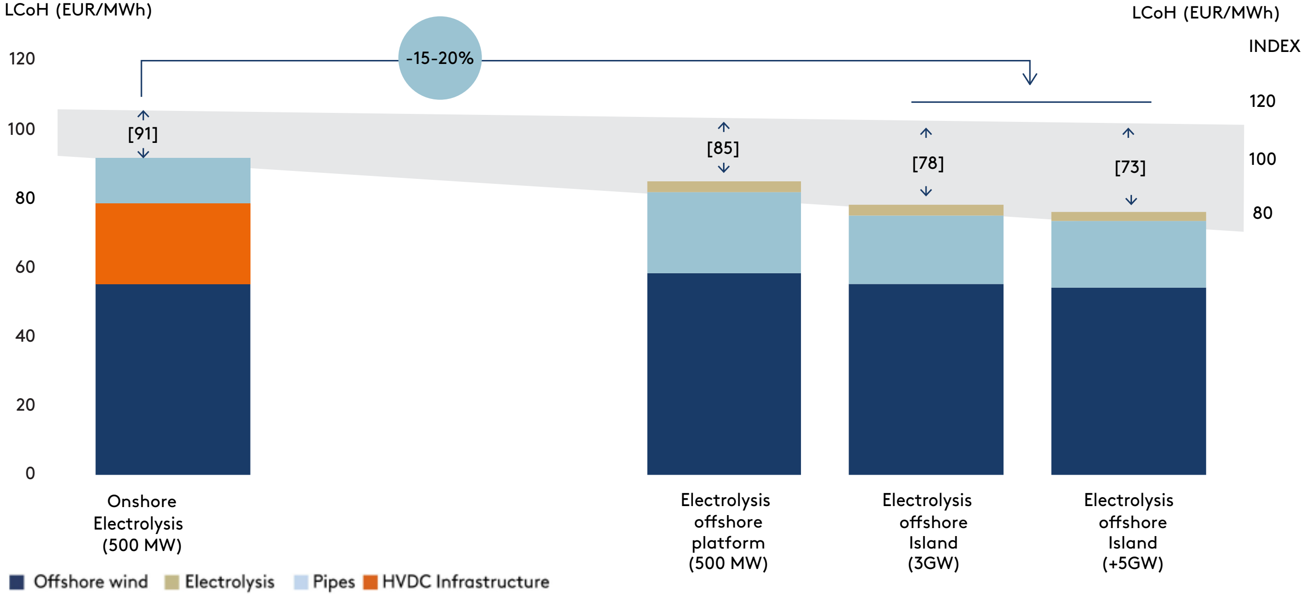
1.6. Denmark in a unique export position

The combination of a strong demand for imported hydrogen in Denmark's neighbouring countries and the aspect that Denmark will soon become self-sufficient in green hydrogen generates a unique export opportunity for this country. If Denmark exploits all of the sites screened for renewable energy, the country's annual exports could reach about 200 TWh after deduction of domestic consumption[12]. This is equivalent to all of Germany's consumption of hydrogen valued at about EUR 13.5 billion a year in income from exports of renewable energy. At the same time it is also considerably less that the forecast demand from Denmark's closest neighbours.

To realise this potential, a hydrogen infrastructure has to be organised and established for the transport of the hydrogen, and also a market design has to be developed for especially the North Sea to facilitate the establishment of large-scale hydrogen production, for example by constructing commercial hydrogen islands.

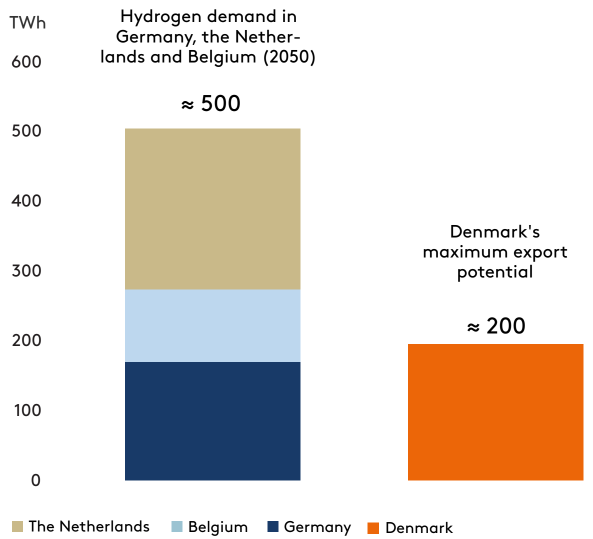
10 Brinckmann (2023)
11 Brinckmann (2023)
12 COWI (2023a)

Figure 1.6: *The cost benefits of hydrogen production are largest for offshore energy islands*



Source: Brinckmann (2023)

Figure 1.7: *Long-term hydrogen demand compared with Denmark's maximum export potential (TWh)*



Source: COWI (2022)

Note: The Danish export potential is calculated as the possible hydrogen production based on the largest possible expansion of renewable energy by screened areas in Denmark and electrolysis capacity deducting Denmark's forecast domestic consumption for 2050. The hydrogen demand in Germany, the Netherlands and Belgium is calculated using the transition potential in these countries in view of their industry structures, expected economic developments etc.

What steps are the EU and other countries taking to develop the hydrogen market?

Chapter 2

A high number of countries have spotted the potential of green hydrogen. Several of Denmark's closest neighbours have a declared need to import green hydrogen and their plans for the expansion of the infrastructure are more advanced than Denmark's, also when it comes to international pipelines and offshore pipelines. Their possibilities for converting an existing natural gas network into a hydrogen infrastructure are also better since Denmark will have to start from scratch in most areas. The EU has set in motion the development of framework regulations along with multiple green hydrogen support programmes which other countries seem to make use of to a higher degree than Denmark.

2.1. Political targets and strategies for the green hydrogen market

A condition for fulfilment of the UN net zero emissions climate target by 2030 is that hydrogen and Power-to-X (PtX) products are produced and for this to come about a minimum of 700 GW would have to be installed at world level by 2030, according to the IEA (2022).

Since global electrolysis installations totalled about 1.4 GW by the end of 2022, according to the IEA, this would require exponential growth of the capacity over the next few years, which is hardly realistic. Today, global electrolysis installations total about 3.5 GW, of which about half is located in Europe, according to Topsoe. The EU's strategic target is for a minimum of 6 GW electrolysis capacity to be installed within the EU by 2024 (EPRS, 2021).

GREAT EU AMBITIONS FOR GREEN HYDROGEN

With its REPowerEU strategy the EU holds great ambitions for an expansion of renewable energy and hydrogen production. As early as 2030, the aim is to produce 10 million tons of hydrogen within the EU and import similar quantities, corresponding to a total hydrogen consumption within the EU of 20 million tons of hydrogen or just short of 700 TWh. This will require an 80 GW electrolysis capacity within the EU by 2030[1] to be used for the production of hydrogenbased on 14% of the EU's overall electricity consumption. The fulfilment of this target will require both a highly notable expansion of the renewable energy production and also an expansion of the electrolysis capacity of absolutely extraordinary proportions corresponding to almost 50 times the currently installed electrolysis capacity in Europe towards 2030. The European Commission (2023b) assumes that the production of 10 million tons of hydrogen will need investments to the tune of EUR 335-471 billion, of which about 60% will be invested in the expansion of renewable energy for the production of the hydrogen.

The latest Ostend Declaration[2] of 24 April 2023 gives rise to the ambition for the North Sea to expand the renewable energy to 120 GW by 2030, increasing to 300 GW by 2050; to this should be added the establishment of about 30 GW electrolysis capacity.

The relatively high demand for self-sufficiency and the highly notable upscaling of the renewable energy and the electrolysis capacity must be viewed in the light of the new geopolitical situation and serves to show that the European energy policy has also become a matter of security policy and industrial policy.

MANY COUNTRIES HAVE DEVELOPED HYDROGEN STRATEGIES SETTING POLITICAL TARGETS

The EU adopted its hydrogen strategy in 2020 which specifies that hydrogen is one of the cornerstones in achieving climate neutrality in the EU by 2030. Since then, hydrogen has also become a critical factor in the REPowerEU plan to make the EU independent from Russian fossil fuels. A number of countries have also adopted national hydrogen strategies in order to paint a clear picture and set the framework for businesses and potential investors that either wish to produce or consume hydrogen and PtX products. With its 2021 PtX strategy, Denmark was not among the first movers in the EU, nor among the last movers either, see Table 2.1.

Also, other countries outside the EU have the potential to produce green hydrogen, either for direct consumption or for processing into PtX products. As an example, Australia can produce large quantities of renewable energy, both solar- and wind-based, and similarly the US has made a strategic choice to ensure the building and industrialisation of PtX as a critical element in the country's efforts to fulfil its climate targets but also with a view to exports based on large support programmes through the Inflation Reduction Act[3]. Several of the countries on the Arabian Peninsula are also in the process of developing solar-to-hydrogen production where Oman, among others, has the ambition to become the world's largest producer of green hydrogen by 2030.

1 Previously, the EU targeted a 40 GW expansion of its electrolysis capacity by 2030 in its Fit for 55 strategy but has since then heightened its ambition.
2 Covers Belgium, the Netherlands, the UK, Luxembourg, France, Norway, Ireland and Denmark.
3 See the CIP Foundation (2023) for a detailed description and a comparison of the costs with hydrogen produced in Denmark.

Denmark's target is a 4-6 GW electrolysis capacity by 2030, slighter more than that of the Netherlands and about half of Germany's forecast for 2030. Although Germany has great plans for its expansion of renewable energy and electrolysis capacity, the country is expecting a consumption of proportions that will force it to import large quantities of hydrogen. Importing hydrogen is a declared political target not only for Germany, the Netherlands and Belgium (discussed in detail by the CIP Foundation, 2023) but also for Austria, the Czech Republic and Slovakia. Mostly because they do not expect to have sufficient renewable energy to produce green hydrogen and green fuels in the quantities required for the green transition. Other larger European countries will also rely on cross-border trade to cover hydrogen requirements.

Contrary to several of Denmark's closest neighbours, a more diverse picture of Sweden's hydrogen consumption and production options emerges. According to the draft national fossil-free hydrogen strategy for Sweden, which was published by the Swedish Energy Agency in 2021, the target is to be self-sufficient in hydrogen and fossil fuels by 2045[4]. This strategy relies on the development of a national value chain for the production, storage and distribution of hydrogen, mostly for domestic consumption.

However, according to the strategy, Sweden also ought to assess its options for becoming a net exporter of hydrogen and ammonia on a regular basis. In view of Sweden's geography and various industry zones and possible sites for renewable energy production, a more regional approach should be expected where some locations will see an import need while other regions may be able to export hydrogen in the absence of an extensive, national hydrogen infrastructure. The strategies and the resulting trading patterns serve to demonstrate the need for a European hydrogen infrastructure, not only at country level but also across borders.

BLUE HYDROGEN AS A TRANSITIONAL TECHNOLOGY AND IN COMBINATION WITH THE NATURAL GAS NETWORK

Although green hydrogen is the end point and necessary to carry through the green transition, expansion to reach sufficient capacity in a short time poses an immense challenge, and besides time could be of the essence in terms of when various sites will be ready to consume green hydrogen and when the production will be sufficient to meet the demand; in addition to this, also the establishment of a hydrogen pipeline infrastructure is vital.

Although most countries point to green hydrogen as the end point, some countries identify blue hydrogen as a transitional technology. As an example, for a period of time Germany will promote the use of blue hydrogen and import this during a period when the country is transitioning to green hydrogen[5]. As one of the steps towards this goal, Norway and Germany have agreed to install a hydrogen pipeline to transmit blue hydrogen from Norway to Germany through Denmark's territorial waters[6].

As part of its hydrogen approach, the EU is also looking into the possibility of mixing green hydrogen with other forms of low-carbon hydrogen, including blue hydrogen. However, this will require a certification scheme (Guarantee of Origin) for the hydrogen infrastructure.

***Table 2.1:** Examples of national hydrogen strategies and targets*

Country	Hydrogen strategy	Electrolysis target by 2030 (GW)	Anticipated export?	Anticipated import?	Comments
The EU	2020	80 (Earlier 40)		✓	Anticipates 50:50 domestic production and import of hydrogen
Denmark	2021 *(Power-to-X strategy)*	4-6	✓		The Energy Department has set a goal of 7 GW electrolysis by 2030
Examples from nearest neighbouring countries					
Germany	2020	10		✓ (62-82 TWh)	Germany's target for electrolysis capacity is 5 GW by 2030 and 10 GW by 2040. It is currently discussed whether the capacity goal should be 10 GW already by 2030.
The Netherlands	2020	3-4		✓ (64-104 TWh)	
Belgium	2022	-		✓ (20 TWh)	
Sweden		5 GW by 2030 10 GW by 2045 *(proposed)*	-	-	
Examples from other EU countries					
France	2020	6,5	✓	✓	Anticipated import from Spain and export to Germany.
Italy	2021 *(Temporary guidelines)*	5	✓	✓	Import from Northern Africa. Can potentially be exported on to neighbouring countries if hydrogen infrastructure allows.
Spain	2020	4	✓		
Poland	2021	2	-	-	
Examples outside the EU					
Australia	2019	-	✓		Anticipated export to Germany/The EU by maritime ways.
The USA	2022 *(Draft)*	-	✓		Anticipated export of hydrogen due to large subsidies through the IRA. No goal for electrolysis capacity. In September 2022 the U.S. Department of Energy released a draft for a hydrogen strategy (DOE National Clean Hydrogen Strategy and Roadmap) for public consultation.
Oman	2022	-	✓		Has a goal of becoming the biggest producer globally of green hydrogen by 2030. Oman has a goal of producing 1 million tons of green hydrogen by 2030.

Note: Target set by the Netherlands includes production of hydrogen using natural gas and CCUS (blue hydrogen). Source: Market Assessment, the CIP Foundation, U.S. Department of Energy (2022), Ministry of Energy and Minerals (2022), Bloomberg (2023), European Commission (2022b), KEFM (2021), Federal Ministry of Economic Affairs and Energy (2020), Ministry of Economic Affairs and Climate Policy (2020), Economie (2022), the Swedish Energy Agency (2021), CMS Expert Guides (Italy), Gouvernement (2020), International Trade Administration (2022), Department of Climate Change, Energy, the Environment and Water (2019), Mark R. Warner (2022).

Technically it is also possible to mix hydrogen into the natural gas network (up to 10% without major modifications, according to the Danish Energy Agency, 2021) which could help ease the transition from when the first production is ready and until a coherent hydrogen infrastructure has been established, although the price of producing green hydrogen is higher than for the fossil-based natural gas.

2.2 Regulation and framework for a future green hydrogen market in the EU

At EU level regulation of the future green hydrogen market is on the way, and through the Renewable Hydrogen Framework legislative efforts are being made.

4 The Swedish Energy Agency (2021).
5 The Oxford Institute for Energy Studies (2020).
6 The Norwegian Government (2023) and also Gasco and Equinor.

With its Hydrogen and Decarbonised Gas Markets Package of 15 December 2021, the European Commission has presented the overall framework of the hydrogen market currently being negotiated. In February 2023, the European Commission, as the latest step, also submitted two delegated acts based on renewable energy directives to the European Parliament for its approval. These acts lay down a number of principles and common minimum standards for the future market.

With the Hydrogen and Decarbonised Gas Markets Package, the regulatory aspects are based on the regulation of gas and a revision of several parts of the Gas Directive while at the same time also coordinating with electricity regulation rules.

EU REGULATION OF THE FUTURE HYDROGEN MARKET BASED ON PRINCIPLES AND A GRADUAL PHASING IN

The principles of the future hydrogen regulation are based on a gradual phasing-in period with the rules being rather flexible to start with and gradually becoming increasingly stringent over time (2030/2035) in a dynamic regulation process. Basically, the hydrogen market is new and under development and so needs some measure of regulatory freedom, although certain common minimum rules are required during the phasing-in period to be supplemented with national legislation.

In parallel with this, the course is set for regulation at some point into the future when the market is more mature. This way the EU wants to ensure maximum flexibility during the first stages when the market is emerging while at the same time providing some measure of investor security as regards the direction of the market, see Table 2.2.

As an important principle for the coming hydrogen market, the green hydrogen must be based on additional renewable energy, i.e., the renewable energy capacity must be expanded more or less to the same tune as the hydrogen production so that the need for electricity to produce hydrogen will not push up prices for the direct electrification process. This principle will take effect from 1 January 2028 to allow a period for expansion of the electrolysis capacity, and then in the period up to 1 January 2030, it will be enforced to enable the hydrogen producers to reconcile their additional consumption of renewable energy on a monthly basis.

> *Renewable hydrogen is a crucial component of our strategy for a cost-effective clean energy transition and to get rid of Russian fossil fuels in some industrial processes. Clear rules and a reliable certification system are key for this emerging market to develop and establish itself in Europe. These delegated acts provide much-needed legal certainty to investors and will further boost the EU's industrial leadership in this green sector."*
>
> *Kadri Simson, EU Energy Commisionar 13th of February 2023*

After this phase, the market is to match on an hourly basis[7].

The same staged approach in step with the envisaged market development is used when it comes to third party access to privately owned hydrogen infrastructure (natural monopoly) which until 2030 can take place on negotiated terms and after that access will be regulated, i.e. the prices (tariffs) for the use of the infrastructure will be subject to approval and control just like the access conditions as such must comply with certain rules and complaints can be lodged.

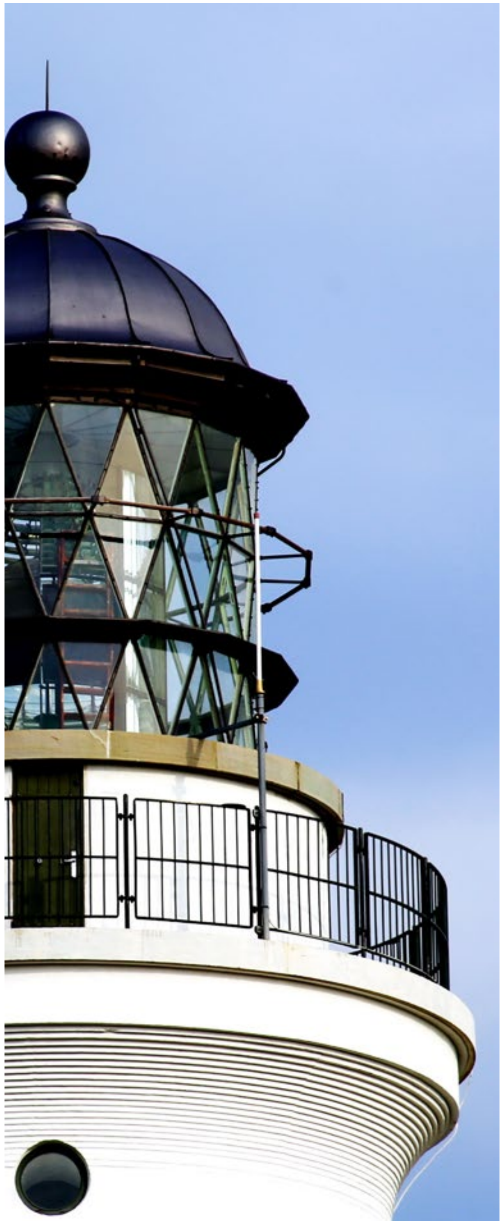
The tariffs (user payment for access to and transport within the infrastructure) must be true to costs, and tariff discounts on green hydrogen or low-carbon hydrogen must be possible (up to 75% on connection and capacity-based tariffs and in connection with storage[8]).

Since the focus is on ensuring that access barriers to hydrogen transport must be dismantled, to the extent possible, the intention is that hydrogen should be allowed to cross borders free of charge (no cross-border tariffs). As a result of this, any expenses of managing pressure differences, temporary storage requirements etc. when shifting from the hydrogen network in one country to that in another country must be paid by the producer and/or the buyers/consumers of the hydrogen.

***Table 2.2:** Principles for EU regulation of the future green hydrogen market*

Phasing-in of regulation	Regulation designed for a mature market is not appropriate for a start-up market which needs an 'evolutive and adaptive regulatory approach.' An interim and relatively lose framework up to 2030 is proposed and then to be replaced by more specific regulations.
Common minimum rules across borders.	To begin with the countries can set up their own, more specific regulations, although in compliance with certain minimum standards.
Additionality	By definition, green hydrogen must be based on additional renewable energy with the result that the PtX production does not result in price increases for the direct electrification.
Non-discriminatory third party access	In the period up to 2030, negotiated third party access is recommended (to be agreed by the commercial parties) and then specific rules will be laid down for regulated third party access.
True to cost and market compatible network tariffs with discount options	Over time, the tariffs must cover the associated costs although with an option for green hydrogen (or low-carbon hydrogen) for up to a 75% discount on connection and capacity-based tariffs and storage in competition with for example grey hydrogen.
No cross-border tariffs	Transporting hydrogen across borders should be free of charge. Consequently, the costs of pressure modifications etc. when crossing borders must implicitly be borne by the producers and/or the buyers/consumers.
Separate ownership of the gas infrastructure and the hydrogen infrastructure	Unbundling of potential owners/network operators to ensure that natural gas infrastructure owners are separated from the future hydrogen infrastructure owners and to avoid ownership across the value chain.
Guarantees of Origin and a certification scheme	It must be possible to separate green hydrogen from other forms of hydrogen (low-carbon hydrogen types) for use as a green fuel through Guarantees of Origin and a voluntary certification scheme.
Development of network codes	Some sort of 'traffic rules' for the hydrogen traffic comprising development of technical requirements for interconnections, system operation, capacity allocation, balancing and bottleneck management.

7 Delegated act for Renewable Energy Directive (EU) from January 2023.
8 Reed Smith (2022).



The EU has also announced that there must be separate ownership of the gas infrastructure and the hydrogen infrastructure, separate ownership of production and distribution networks and throughout the value chain (unbundling) to the effect that the same player may not operate several components.

This might pose a challenge as the sectors of the two forms of energy, natural gas and hydrogen, are to be connected and the existing natural gas pipelines retrofitted. This has resulted in some challenges in the Netherlands, among other places[9], where the existing gas TSO, Gasunie, as already discussed has been entrusted with the job to expand the hydrogen infrastructure, which involves very considerable reuse of the natural gas network. The Netherlandish Minister for Climate and Energy, Rob Jetten, has stated that going forward, Gasunie's subsidiary, HyNetwork Services, will be managing the development of a hydrogen infrastructure[10]. This also minimises the possibility of cross-subsidisation between the networks.

With green hydrogen (and other forms of low-carbon hydrogen), the hydrogen market will also need a Guarantee of Origin if green hydrogen is to become a commercial product. For this reason, the European Commission has initiated a voluntary certification scheme where CertifHy™ produces the harmonised Certificate of Origin which, among other purposes, classifies hydrogen as a fuel produced using renewable energy which is not based on biomass (renewable fuels of non-biological origin, RFNBO) thereby paving the way for green hydrogen to be used in the transport sector.

For the purpose of the coming hydrogen market, the European Commission will also develop network codes or technical requirements that will support harmonisation/standardisation and integration across the European hydrogen market, and which will support the efficient exchange of energy. The network codes concern technical requirements to interconnections, market conditions (capacity allocation, balancing and bottleneck management), system operation and cyber security. They are known from, for instance, electricity regulation where they are developed by ENTSO-E based on input from ACER (Agency for Cooperation of Energy Regulators). The network codes are a binding regulatory measure.

Both EU legislation and bills for Danish legislation suggest that hydrogen should be regulated based on the gas regulation existing today[11] and otherwise coordinated with the regulation of the electricity production. Since the gas regulation must be revised and the incentives must be adjusted to match the future hydrogen market, the regulation measures cannot be copied one to one.

FUTURE HYDROGEN REGULATION TO BE BASED ON GAS REGULATION PRINCIPLES

The regulation of gas transmission allows for the circumstance that the gas market is a mature market with, among other things, inherent incentives to use the overall capacity of the infrastructure in an optimal way and avoid ''congestion periods' through capacity-based tariffs, see Table 2.3. This could also be relevant for a future hydrogen market.

Various regulatory incentives are in place for European gas transport. For example, there is a discount if the users of the network (in the supply contract) accept to be disconnected, i.e., the gas authority buys the right to interrupt the gas supply in full or in part if the gas network reaches a certain crisis level. This will enable the authorities to reduce the demand during critical supply situations and maintain the gas supply for other consumers with an uninterruptible need for a longer period of time.

REGULATION OF ELECTRICITY TO AFFECT THE FUTURE HYROGEN MARKET

Several countries are in the process of preparing the regulation of the electricity market for the future hydrogen and PtX production which will require huge quantities of renewable energy.

Since by far most of the operating costs of producing green hydrogen are the result of the price of green electricity, the electricity price as well as the relevant tariffs, duties etc. are also of great importance to the profitability of the hydrogen production.

Germany offers an exemption to large consumers, such as PtX producers, from paying tariffs based on their use of the common electricity grid for the first 20 years as a start-up subsidy for a new market (Table 2.3). Other countries also offer large consumers various forms of discount.

Compared with Denmark's neighbouring countries, tariff payment in Denmark will become increasingly important as the PtX market grows, and differences in electricity

9 A Transmission System Operator (TSO) is a grid or network operator tasked with transporting energy (typically gas or electricity) at national or regional level using a permanent infrastructure. A TSO can be a state-owned or private operator. In Denmark, the TSO for electricity and gas is the state-owned enterprise Energinet. Being an infrastructure operator, Energinet plans, funds and carries out the development of the energy infrastructure within these areas, supported by a government guarantee. Energinet's strategic long-term development plans for the electricity sector are subject to parliamentary approval whereas the development of the gas transmission network is subject to approval by the Minister for Climate, Energy and Utilities.
10 Ministerie van Economische Zaken en Klimaat (2022).
11 Reed Smith

***Table 2.3:** Tariff structure for transmission of gas in Denmark and neighbouring countries*

TSO	Volumetric	Capacity based	Discount to/ from storage	Interruptibility discount
Denmark	✗	✗	✓ (100/100%)	✓ (5-10%)
The Netherlands	✗	✓	✓ (60/60%)	✗
Germany	✗	✓	✓ (75/75%)	✓
Belgium	✓ (3%)	✓ (97%)	✓ (100/50%)	✓ (20%)
Sweden	✓ (20%)	✓ (80%)	✗	✗

Source: Copenhagen Economics (2022a)

Incentive-based tariffs that take into consideration the consumption compared with the overall capacity are also relevant for a future hydrogen infrastructure – both for periods with little use of the pipeline when incentives are required to increase the use and for the time when the market has become more advanced and where added pressure is a condition for transport.

and hydrogen tariffs can become a competitive parameter in the European hydrogen market of the future[12]. At this point in time, most Northern and Western European countries charge lower tariffs from potential hydrogen and PtX producers than Denmark, see Table 2.4.

Looking at the new regulation trends for the EU gas and electricity markets as a whole, Copenhagen Economics highlights a few general trends:

- More long-term and transparent investments based on long-term development plans, among others;
- More cost-based tariffs;
- Mixed ownership through the value chain.

DEVELOPMENT OF HYDROGEN MARKET AFFECTED BY SEVERAL REGULATIONS

As is evident, a range of regulations need to be developed and adapted to support the future green hydrogen market and also several support programmes exist. As an example, the EU CO2 quota system (ETS) sets a price for CO2 emissions with regular lowering of the emissions ceiling for the quota sector.

***Table 2.4:** Denmark charges the highest electricity tariffs from PtX consumers/large consumers*

Country	Electricity tariff for PtX/ big costumers
Denmark	15 EUR/MWh
Germany	0 EUR/MWh After 20 years: ≈ 16 EUR/ MWh
The Netherlands	4 EUR/MWh
Sweden	3 EUR/MWh
Finland	≈ 5 EUR/MWh

Source: Copenhagen Economics (2022a)

In future, maritime shipping will become part of the system. In parallel with this, the mixing requirements for fuels will be intensified; sustainable fuels, not based on biomass[13], including green hydrogen, are to make up 2.6% of the transport sector's consumption by 2030. Furthermore, requirements will also be proposed for the individual sectors, according to which the manufacturing industry must reduce its consumption of grey hydrogen by 50% and replace it with green hydrogen.

2.3 Other initiatives promoting hydrogen

The EU has allocated considerable funds to promote research, development and implementation of green hydrogen technology and to support investments in electrolysis capacity and infrastructure. To this should be added measures at national level.

An important component of this effort is the Horizon Europe programme, among others, which is the EU's largest research and innovation programme. Horizon Europe funds projects and initiatives focusing on developing the use of green technologies, including PtX technologies and green hydrogen. Through this, the EU supports research institutions, business enterprises and organisations in their efforts to develop and test hydrogen technologies and upscale their production. As an example, the North Adriatic Hydrogen Valley, a joint hydrogen project involving Slovenia, Croatia and Italy, has received EUR 25 million in funding from Horizon Europe.

The funds are spent on green hydrogen production pilot projects in the three countries with the purpose of creating a common value chain[14].

***Figure 2.1:** The EU framework for the development of green hydrogen*

Source: Windeurope (2022)

12 Tariffs are the fees paid for use of the electricity grid and is settled between Energinet and the electricity supplier.
13 Renewable Fuels of Non-Biological Origin (RFNBOs).
14 HSE (2023)

In addition to research and development, the EU and the EU Member States have set up partnerships to promote the use of green hydrogen. An example is the European Clean Hydrogen Alliance which was launched in 2020. This alliance joins together business enterprises, research institutions and governments with the purpose of speeding up the development, enhancing the demand and upscaling the use of green hydrogen. Through this collaborative effort, the EU encourages investments in green hydrogen infrastructure and supports the development of a European hydrogen market. The focal point of the alliance is to ensure that this issue is given high priority and access to funding[15].

SUPPORTING PROJECTS OF STRATEGIC IMPORTANCE TO THE EU

Support for investment and funding also comes via the Important Projects of Common European Interest (IPCEIs) programme for hydrogen.

The first IPCEI programme, HY2Tech, was granted approval in June 2022 and provided support to 41 projects aiming to develop technologies for the hydrogen value chain. In September 2022, the second programme, Hy2Use, was granted approval by the European Commission and the purpose of this programme is to support the construction of a hydrogen-related infrastructure and the development of technologies for the integration of hydrogen into the industrial sector. These two IPCEI programmes procure EUR 1.4 billion in subsidised funding which is expected to release EUR 15.8 m from private sources, according to the European Commission (2023). The IPCEI projects are exempted from the EU's standard state support rules and processes.

Within the framework of the EU support programmes, also other options are available for supporting infrastructure projects related to hydrogen through Projects of Common Interest (PCI). IPCEI is a broader initiative covering different sectors and technologies, through different programmes, whereas PCI more specifically focuses on energy infrastructure.

IPCEI support requires the participation of minimum two EU Member States, and the project must have appropriate representation of EU territory. Several EU Member States may be involved in PCI projects although this is not a prerequisite for funding.

The joint declaration of March 2023 between Denmark and Germany concerning an onshore hydrogen connection states that both countries will apply for funding in order to acquire support via the PCI support programme[16].

Apart from this, Denmark (and Danish enterprises) has only applied for this type of EU funds to promote hydrogen production and infrastructure to a limited extent. In 2022, the Danish project Green Fuels for Denmark was awarded EUR 80 million as part of Denmark's participation in the IPCEI programme Hy2Tech, according to Ørsted (2022).

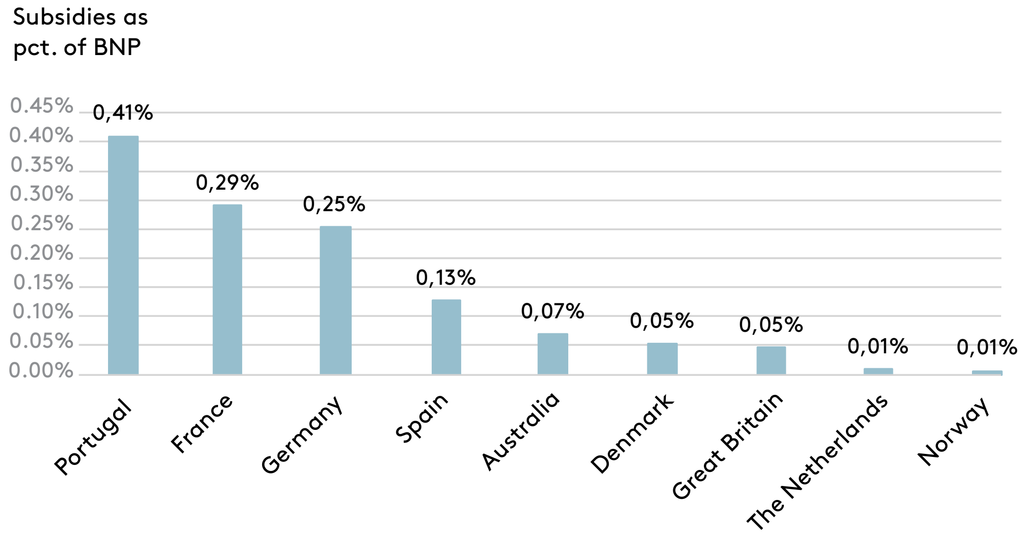
This was the only Danish project. Relatively speaking, Denmark has generally received only few IPCEI funds compared with several other European countries. A number of French projects were for instance part of the implementation of Hy2Tech[17]. The implementation of IPCEI Hy2Use again comprised only a single Danish project, Everfuels, whereas especially Spanish projects were included in Hy2Use[18]. The few applications for funding submitted by Denmark is noteworthy, considering the large potential Denmark has for combining renewable energy with hydrogen production compared with other countries.

EUROPEAN HYDROGEN BANK SUPPORTS PRIVATE HYDROGEN INVESTMENTS, FOR EXAMPLE THROUGH FIXED PRICE SCHEMES

With its 2023 work programme, the EU has launched the European Hydrogen Bank which is to help mobilise private investments by reducing risks, creating transparency and offering funding on competitive terms.

The purpose is to close the cost gap between the production of green hydrogen and fossil-based hydrogen during the initial phase[19]. In practice, a programme is proposed with a fixed price per kilogram of hydrogen for a period of maximum 10 years to be auctioned off (auctions-as-a-service). The first pilot auction is set for the autumn of 2023. The bank will also contribute by building expertise and knowledge about hydrogen projects and their financial viability. This initiative is under development and the bank will be operational by the end of 2023. The European Hydrogen Bank is backed by EUR 800 m from the EU Innovation Fund, among others. As part of its response to the US hydrogen production subsidies (the US Inflation Reduction Act – IRA), the EU has also discussed the possibility of setting up a Sovereignty Fund. This fund could, for instance, offer funding directly to companies that are setting up hydrogen production and respond faster than when pool schemes and similar initiatives are set up. EU Commissioner Margrethe Vestager emphasises that the investment fund concept could be set up via the European Investment Bank (EIB), as an example[20].

Figure 2.2: *The national framework for the development of green hydrogen*



Note: The targets set by the Netherlands and the UK also include blue hydrogen. The funds allocated by Germany also include funds for infrastructure.
Source: Kraka Advisory (2023) and own calculations based on Statistics Denmark

15 The European Commission
16 The Ministry of Climate, Energy and Utilities (2023b)
17 The European Commission (2022c)
18 The European Commission (2022d)
19 The European Commission (2023b)
20 Børsen, 12 May 2023.

NATIONAL FUNDS FOR ELECTROLYSIS TARGETS

In addition to EU funds, several countries have also set aside funds for support and development of the value chain for hydrogen and other green fuels at national levels. Several countries, inside and also outside the EU, have set aside considerably larger sums than Denmark to achieve almost the same capacity targets. In the EU, especially Germany, Spain and France have allocated large sums to building PtX production and infrastructure (Figure 2.2).

France is, for example, planning to offer EUR 7 billion in public subsidies until 2030 for R&D, start-ups and industrialisation and market start-up, according to its national hydrogen strategy[21]. Overall, France has allocated EUR 7.2 billion to this purpose. France has set a target for its electrolysis capacity of 6.5 GW, whereas Denmark is targeting 4-6 GW. By way of comparison, Denmark has allocated EUR 0.17 billion with the Government's PtX strategy. Kraka Advisory has produced a list of funds allocated to the promotion of electrolysis by selected countries. On the face of it, Germany has set aside the largest sums.

***Box 2.1:** Several countries enter collaboration agreements with other countries*

Examples of collaboration agreements

A number of collaboration agreements have been concluded between countries that wish to secure supplies or sell excess resources

Country	With	Type	Comment
The EU	Egypt	Hydrogen	By signing a Memorandum of Understanding (MoU), the European Commission has pledged to invest EUR 300 million in the development of the country's hydrogen production
Denmark	Belgium	Electricity	Interconnection from Danish energy island in the North Sea to Belgium
Denmark	The Netherlands	NA	Offshore interconnection between Denmark and the Netherlands
Germany	Morocco	Hydrogen	Germany is to invest EUR 300 million in order to be able to make a claim on the future import of hydrogen
The Netherlands	Portugal	Hydrogen	MoU signed concerning the development of a strategic value chain
Belgium	Chile	Hydrogen	MoU signed concerning the green hydrogen import value chain
Germany	France, Spain Portugal	Hydrogen	MoU signed concerning the development of a joint hydrogen infrastructure
Germany, The Netherlands	The United Arab Emirates	Hydrogen	Development of a blue hydrogen interconnection between the EU and the Middle East
Germany	Australia	Hydrogen	MoU signed concerning the development of a value chain between German E.ON and an Australian green hydrogen supplier. The target is 5 m tons of hydrogen a year by 2030, corresponding to one third of Germany's previous imports from Russia.

Source: The European Commission (2022); Wind Europe (2021); Port of Antwerp Bruges (2021); Market Assessment, the CIP Foundation (2023); KEFM (2023)

Considering the size of these countries, Portugal, however, has allocated the highest sum for electrolysis, relatively speaking, setting aside EUR 0.89 billion for the promotion of electrolysis capacity in view of a target to reach a capacity of between 2 and 2.5 GW by 2030[22]. By comparison, Denmark has so far set aside EUR 0.17 billion for the construction of an electrolysis capacity of between 4 and 6 GWh. Germany has set aside a total of EUR 8.9 billion and is targeting an electrolysis capacity of 10 GW[23], which is considerably more than the remaining European countries (Table 1). The total funding is the sum of several measures. As an example, the German Government decided in the summer of 2021 to allocate EUR 8 billion in subsidies for 62 hydrogen projects, according to BMDV (2021). The allocation of large sums is not only a sign of a desire to live up to climate targets but also of a need to secure imports from other countries due to the limited quantity of domestic renewable energy for PtX production.

Outside of the EU, especially the Inflation Reduction Act (IRA) adopted by the US has attracted attention. The IRA is financially beneficial to especially green hydrogen producers who are expected to be able to cut away half of the price of their green hydrogen production from a short-term perspective. The funding regimes for green hydrogen producers included in the IRA are so considerable that potentially the IRA could give US hydrogen a competitive advantage over Danish hydrogen, see the Market Assessment of the CIP Foundation (2023).

PARTNERSHIPS AND COLLABORATION AGREEMENTS BOTH WITHIN AND OUTSIDE THE EU

Germany has set aside EUR 2 billion as part of the German hydrogen strategy for the establishment of international partnerships in order to secure the supply of blue as well as

21 Gouvernement (2020)
22 CSIRO
23 The officially identified target is 5 GW although a future revision of the hydrogen strategy suggests an upward adjustment to 10 GW by 2030.

green hydrogen. Germany has already formed a number of partnerships with countries such as Morocco, the United Arab Emirates and Australia. Denmark has also formed a partnership with Germany with the intention to analyse joint offshore energy projects and hybrid offshore energy projects in 2020 in a collaborative effort and a hydrogen pipeline across the Danish-German border in 2023.

The Netherlands and Belgium are also looking towards other countries to secure supplies and imports of both electricity and hydrogen. What these collaboration agreements express is a desire to secure the supply for the green hydrogen buyers and consumers with the result that the first steps of the transition process, for example by the manufacturing industry, can be taken more safely.

In view of Denmark's large potential for producing renewable energy (and with this also hydrogen and PtX products) far in excess of the country's own requirements, a relatively low number of collaboration agreements have been entered into between Denmark and other countries. One reason for this could be that governments are more proactive when it comes to fulfilling domestic requirements rather than when it comes to selling the country's own resources to others.

Denmark's opportunities to provide neighbouring countries with renewable energy and hydrogen are not only a question of export gains, however, it is also a question of reducing climate emissions in the immediate vicinity of Denmark and supporting Europe's energy independence. To this should be added that the collaboration agreements in fact follow up on the political targets and declarations, for example the Esbjerg Declaration, the Marienborg Declaration and most recently the Ostend Declaration.

2.4. The hydrogen infrastructure of today and tomorrow

Today about 5,000[24] km of hydrogen pipeline infrastructure exists in the US, Germany, Belgium and the Netherlands, to name a few. This carries fossil-based hydrogen (grey hydrogen) – often from production facilities or port infrastructures directly for industrial purposes and in the form of closed distribution networks in private ownership.

The most extensive structure in Europe is found in Belgium which has a 613 km hydrogen infrastructure centred around major industrial hubs, such as Antwerp and Gent. Germany comes in second with about 400 km of dedicated hydrogen infrastructure. According to Copenhagen Economics, the existing hydrogen infrastructure in Northern Europe is similar to private pipelines in the sense that tariffs are not charged, and incentive-inducing regulations do not apply to them, but negotiations are on-going to include them in the common supply network.

REUSE OF EXISTING NATURAL GAS NETWORKS MAKES EXPANSION EASIER

In addition to using existing hydrogen networks for green hydrogen, the natural gas network can also be retrofitted to carry hydrogen. According to EPRS (2021), a number of studies show that reuse of existing gas infrastructures is more cost-effective than expanding the electricity grid and go for more direct electrification to support the green transition.

This is especially relevant in countries such as Germany, the Netherlands and Belgium whose natural gas networks extensively consist of dual pipelines allowing gas to be transmitted in both directions over a distance.

As fossil natural gas is being phased out, transport needs will drop with the result that one of the pipelines can be converted into hydrogen. The option to reuse gas pipelines is one of the reasons why hydrogen is found to be particularly relevant and cost-effective in the green transition of the energy-intensive industry.

In the Netherlands, the state-owned gas infrastructure operator, Gasunie, has been tasked with the construction of a hydrogen network by converting 85% of the existing natural gas network into hydrogen pipes which are to be ready for operation by 2027[25].

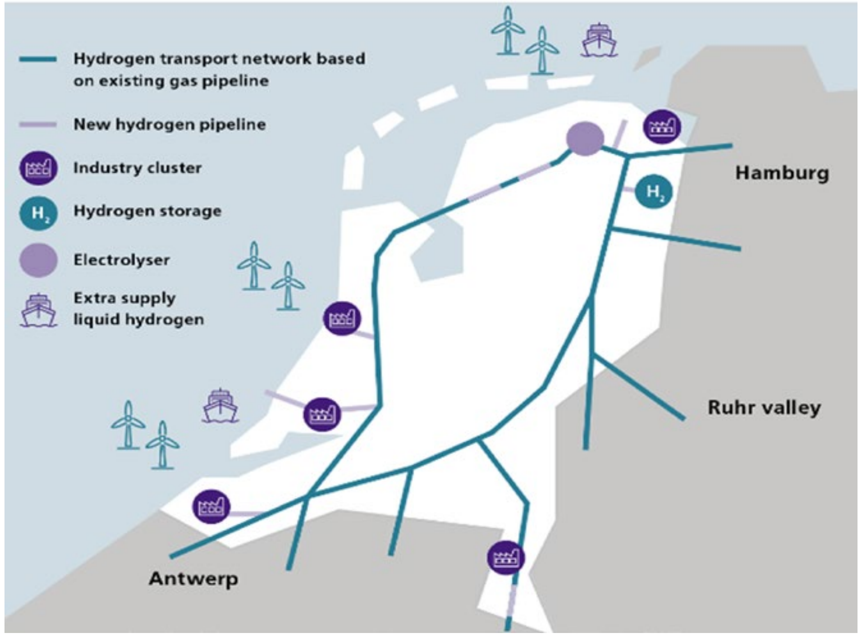
The Netherlands is among the frontrunners when it comes to developing a future hydrogen infrastructure, and Gasunie has drawn up the overall layout of a hydrogen infrastructure which will link neighbouring countries, consumers and producers and with the first section to be rolled out in 2025/2026, which also Figure 2.3 shows.

The idea is to build a circular network (backbone) which will form an interconnection between five different industrial clusters producing and consuming hydrogen with ports and storage facilities. In Europe, between 60% and 80% of the hydrogen infrastructure is expected to be made up of upgraded gas pipes, according to Brinckmann (2023).

THE NEED TO BUILD A NEW HYDROGEN INFRASTRUCTURE IS ESPECIALLY LARGE IN THE NORDIC COUNTRIES

In countries such as Denmark, Sweden and Finland most of the natural gas network is made up of single pipes, which in effect

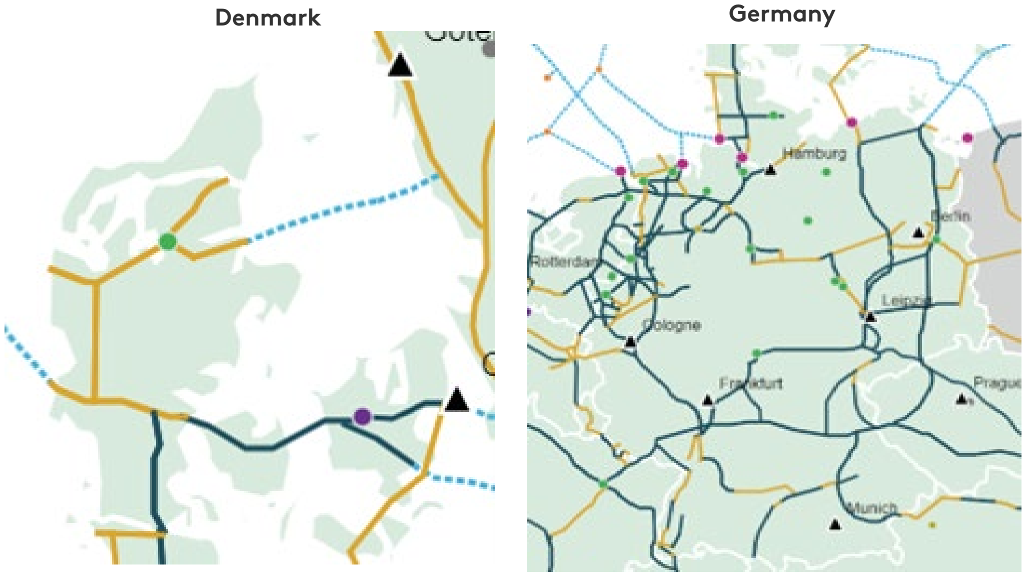
Figure 2.3: *Onshore hydrogen infrastructure planned in the Netherlands*



Source: Gasunie (2022)

24 This should be viewed relative to the total gas infrastructure globally which is about 3 million km (ERPS, 2021).
25 FuelCellsWorks (2022) and Gasuine (2022).

***Figure 2.4:** Reused and new installations in Denmark and Germany*



Note: Yellow indicates new pipelines, dark blue reused pipelines and blue offshore pipelines.
Source: The European Hydrogen Backbone

makes it impossible to reuse the gas pipes as long as they are used to transport natural gas and biogas[26]. In these areas much of the hydrogen pipeline structure will have to be based on new pipes.

A PLAN FOR THE FIRST INTERNATIONAL PIPELINE FROM DENMARK TO GERMANY

A national plan for the construction of a hydrogen infrastructure does not yet exist for Denmark, neither onshore nor offshore.

As a first step, Denmark has agreed with Germany to establish a hydrogen pipeline from Southern Denmark to Germany (the 'lower T' in Figure 2.4). This section also holds one of the few dual-pipe interconnections for natural gas pipes in Denmark, from Egtved to the border. Although only with 30" pipes. The CIP Foundation's proposal involves larger pipes for this key section due to the large transport need in a long-term perspective. On the German side of the border and to Hamburg, about half of this section can actually consist of reused natural gas pipes whereas the rest will be new hydrogen pipes (Gasunie and Energinet, 2021). Coordinating the available capacity at both sides of the border is essential to avoid bottlenecks. A feasibility study of this interconnection has been conducted and the planning of the specific steps is on-going.

The intention of the Danish-German declaration is that the interconnection is to be completed by 2028; however, this will require extensive measures to develop regulations, obtaining capacity commitments from future consumers etc. Use of the interconnection will not become relevant until a complete interconnection has been established from hydrogen producers in Southern Denmark all the way to the buyers/consumers in Germany (to begin with Hamburg). At the same time, feasibility studies of an offshore interconnection from the future Bornholm Energy Island to Germany are being carried out.

COMPREHENSIVE PLANS FOR A COHERENT EUROPEAN HYDROGEN INFRASTRUCTURE

At the moment, a coherent European hydrogen infrastructure does not exist; however, this is critical in order to build a market for green hydrogen and to enable the green transition of especially the energy-intensive industries and transport.

The need for an infrastructure has resulted in several initiatives with countries not only planning a domestic infrastructure but also joining forces with other countries, for example through the European Hydrogen Backbone (EHB). The EHB consists of a group of 32 energy infrastructure operators (TSOs) who want to accelerate the development of the hydrogen market in Europe by defining the hydrogen infrastructure. Danish TSO Energinet is part of this initiative on behalf of Denmark.

The EHB has developed a vision for a cross-border hydrogen infrastructure for all participating countries based on national strategies, planning processes known by the TSOs, announced projects and the TSOs' assessment of the possibilities of reusing the pipelines (see Figure 2.4). The proposed infrastructure is expected to extend 53,000 km before 2040, and the investment in onshore and offshore infrastructure is estimated to total EUR 80-143 milllion, according to the European Hydrogen Backbone (2022).

***Figure 2.4:** Reused and new installations in Denmark and Germany*

Note: Yellow indicates new pipelines, dark blue reused pipelines and blue offshore pipelines.
Source: The European Hydrogen Backbone

26 The biogas network is being expanded in Denmark

Box 2.2: International hydrogen infrastructure in the North Sea

AquaDuctus

AquaDuctus is a 400 km offshore hydrogen pipeline. Initially, the pipeline will extend to Germany, reaching into Belgium and the Netherlands, and will potentially produce renewable energy and hydrogen in the North Sea. The interconnection extends from Germany to relevant offshore wind farms and potential hydrogen production facilities via Helgoland and to Dogger Bank where the pipeline can also be connected to pipelines from other countries, with Denmark being one example.

In January 2023, the two TSOs, GASCADE (Germany) and Fluxys (Belgium), applied the European Commission for funding of a project of common interests under the IPCEI programme. The AquaDuctus infrastructure project is part of a major renewable energy programme, AquaVentus, which comprises both major offshore wind farms and possibly also an energy island.

Sources: Market Assessment, the CIP Foundation (2023)

Box 2.3: International hydrogen infrastructure in the Baltic Sea

THE BALTIC HYDROGEN COLLECTOR IN THE BALTIC SEA AND THE NORDIC HYDROGEN CORRIDOR ALONG THE COAST

In late 2022, the Finnish and Swedish TSOs, Gasgrid Finland and Nordion Energi, together with two industry operators, OX2 and Copenhagen Infrastructure Partners, set in motion a feasibility study of a common Baltic interconnection, known as the Baltic Sea Hydrogen Collector.

The hydrogen pipeline in focus constitutes a large-scale, cross-border collection and transport infrastructure for green hydrogen. The objective of this project is to support a future hydrogen market by interconnecting supply and demand centres in the Bothnian Bay and the Baltic region with Central Europe.

The offshore hydrogen pipeline will form an interconnection between Finland, Sweden and Germany. The pipeline could potentially be connected to the envisaged energy islands on Bornholm, Denmark, and Gotland, Sweden.

An onshore interconnection is also being planned to stretch from Finland and through the Baltic countries and Poland to Germany, the Nordic Hydrogen Corridor, where pre-feasibility studies are being conducted. The cross-border interconnection requires coordination between multiple countries.

Sources: The European Hydrogen Backbone (2022), OX2 (2022), Gasgrid (2023) and Market Assessment, the CIP Foundation (2023).

OTHER COUNTRIES ARE ALSO PLANNING A COMMON OFFSHORE INFRASTRUCTURE
Much of the renewable energy to be supplied to especially Northern Europe is expected to be generated from offshore wind from the North Sea and partly also the Baltic Sea, according to the Marienborg Declaration and the Baltic Declaration.

The intention is to export some of the energy to the shore in the form of green electricity; however, hydrogen could also be produced offshore on energy islands, platforms with electrolysis and from offshore wind turbines integrated with hydrogen production. For this concept, hydrogen pipelines will be a necessary infrastructure.

Germany and the Netherlands are in the process of planning a joint offshore hydrogen infrastructure, AquaDuctus, which reaches into the North Sea from two hydrogen-consuming areas with established hydrogen infrastructures and toward offshore areas which are suitable for the production of large quantities of renewable energy as part of a major construction plan, AquaVentus. The proposed hydrogen infrastructure can also be linked to production and consumption facilities in Norway, the UK and Belgium, and Denmark could potentially become part of it, see Box 2.1.

The Baltic Sea also holds great potential for the production of renewable energy where several countries are joining forces to build a shared offshore interconnection between hydrogen production facilities and buyers/consumers (mostly in Germany) through the Baltic Hydrogen Collector and onshore along the shores of the Baltic countries and through the Nordic Hydrogen Corridor (see Box 2.2).

The cross border hydrogen infrastructure allows for economies of scale and access to multiple markets, which supports the development of the market but also requires coordination across borders and close collaboration between regulatory authorities. The countries producing and exporting hydrogen are forced to include the cross-border interconnections in their design of the national hydrogen infrastructures since this is a prerequisite for the ability to realise the production potential. And also, to include the purchasing markets (consumption and procurement) in the funding of the infrastructure.

Denmark should familiarise itself with the hydrogen infrastructure plans of other countries and where relevant coordinate with and join common hydrogen infrastructures across borders in order to ensure access to the markets, obtain flexibility and access to large-scale projects, which can lower the costs per transported unit of hydrogen.

Box 2.3: *Other examples of hydrogen infrastructure projects*

A Norwegian-German hydrogen pipeline (for blue hydrogen)
In January 2023, the German and Norwegian heads of state announced a collaborative venture, and Gascade and Equinor have set in motion a feasibility study of a Norwegian-German hydrogen pipeline through the North Sea, passing through Danish territorial waters. This hydrogen pipeline is intended to transport blue hydrogen (fossil-based hydrogen offset by CCS (Carbon Capture and Storage)).

A hydrogen pipeline from Portugal through Spain and France reaching into Germany (H2Med)
As part of a major European Green Energy Corridor, Spain, Portugal and France launched the H2Med hydrogen pipeline in early 2022. An application for EU funding of the first section of the project, interconnecting Portugal, Spain and France, was submitted as a Project of Common Interest (PCI) to the EU. Germany joined the project in January 2023. This hydrogen pipeline is to be able to transport up to 2 million tons of hydrogen or about one fifth of the European hydrogen production in 2030 expected by the EU. Part of this interconnection includes an offshore pipeline between Barcelona and Marseille. A Memorandum of Understanding (MoU) was concluded in late 2022 in this respect. According to Reuters, the costs of this offshore interconnection will amount to about EUR 2-3 billion and it will be finalised in 2030.

Examples of agreements on offshore interconnectors (electricity) associated with hydrogen production
Denmark and Belgium have already concluded agreements that aim to realise the 'TritonLink' cable, an electricity cable which will connect the future Danish energy island in the North Sea with either a Belgian energy island (electricity) or the Belgian mainland in 2033. Denmark and Belgium have also agreed to look into the possibilities of building yet another international pipeline after 2033.
With the Ostend Declaration of April 2023, Denmark and Germany launched a collaborative effort concerning the North Sea Energy Island by signing an agreement for the purpose of the two countries looking into the options for connecting the energy island in the North Sea (electricity) to a German offshore hub of about 10 GW.

Sources: The European Hydrogen Backbone (2022), OX2 (2022), La Moncloa (2022) and Market Assessment, the CIP Foundation

PART 1

What is required to set up a hydrogen infrastructure?

A clearly defined regulation for a market under development

Chapter 3

3.1. What form of regulation is required for the hydrogen infrastructure?

By their very nature, a pipeline hydrogen infrastructure and future energy islands, which also produce hydrogen, will be natural monopolies requiring relevant regulation. One example could be to ensure access to it for several consumers (third party access) through cost-based prices.

When used by several parties at the same time, the infrastructure is similar to a common good or public good. In that case, centralised measures are required to overcome the joint action issue that might otherwise arise when different players are to work together to organise a public good.

A characteristic feature of the infrastructure, i.e., hydrogen pipelines, is the lengthy planning and implementation involved which carry huge costs and result in often irreversible physical installations.

Physically, hydrogen is more like natural gas than electricity, and certain aspects of the future hydrogen market will be similar to when the natural gas market was first set up. The green hydrogen market will be characterised by a limited number of start-up businesses for a period of time, and similarly the consumers will be relatively few and large commercial enterprises.

The consumers will either be using the hydrogen directly in their industrial processes (energy-intensive, high-temperature processes), as fuel for transport purposes[1] or as input for processing into PtX products.

Specially to begin with, the price of hydrogen can be expected to be determined through long-term purchase agreements (power purchase agreements – PPAs) like in the gas market, which will ensure reliable sales for some time and help stabilise the start-up period. In return this will also limit future access to the market. With its relatively few market players and high entry costs, the hydrogen market will not be a fully competitive market contrary to the competitive electricity market.

The green hydrogen market, however, is closely linked to the electricity market since the hydrogen is produced using renewable energy, typically wind or solar energy, and this production can play a balancing role for the electricity grid, especially by producing during periods with plenty of fluctuating renewable energy and by limiting the need for expansion and improval of the electricity grid.
When hydrogen starts to play a role in the sector connecting process for the energy market, by linking electricity production with storage options and processing of the hydrogen, the consequence could be that the regulatory collaboration between the energy markets should be given more attention.

For example, the new options with direct pipelines as part of the Danish regulation of the electricity market will also be relevant for a future regulation of hydrogen, and similarly discounts for large-scale electricity consumers and buyers will be relevant for the options open to hydrogen producers who do not have an in-house supply of green electricity in all situations or all the time.

THE FUTURE REGULATION OF THE HYDROGEN MARKET PLAYS SEVERAL ROLES
In view of the above, the future regulatory framework for the production and transmission of hydrogen will have to consider several aspects: The EU and also Denmark are reviewing the option to regulate hydrogen at the general level according to the existing gas regulations in future, as discussed in Chapter 2. However, as can be seen from Figure 3.1, other forms of regulation will also have to allow for green hydrogen.

3.2. An emerging market vs. a mature market

Expectations are that the hydrogen market will be characterised by relatively few producers and few commercial buyers/consumers and to begin with even fewer producers and buyers/consumers since many of the future market players do not yet exist.

Along the same line, the development of the price of green hydrogen is uncertain. Although as time goes, various drivers will narrow the price gap compared to the fossil alternative, which will become relatively more expensive over time, it is uncertain when price convergence between the different types of hydrogen is achieved. To preserve their green profile some companies will be willing to pay a green premium for their input/fuels, and as the political targets of decarbonisation materialise into specific requirements, the demand for green hydrogen for the green transition, among others in Denmark's closest neighbouring countries[2], will become so strong in the absence of obvious alternatives that they will also be more willing to pay.

1 In principle, consumers can also become direct users of hydrogen as a fuel if hydrogen-based refuelling becomes available.
2 See also the Market Assessment of the CIP Foundation (2023).

MORE INTENSE UNCERTAINTY DUE TO INCONSISTENT TIMELINES AND INTERDEPENDENT DECISIONS

To begin with, the green hydrogen market will be characterised by extraordinary uncertainty which is intensified by the circumstance that many of the decisions required to establish the market and the relevant infrastructure are reached through unrelated processes without parallel timelines and yet they are highly interdependent.

When setting up an infrastructure for a new market during its early infancy, especially when it comes to large, capital-intensive investments and irreversible structures, you are faced with the classic 'the chicken or the egg' challenge of what is a condition for what or what should come first:

Is it the provision of an infrastructure (market access) or is it the demand for hydrogen to be transmitted by the infrastructure? From an energy perspective, this is demonstrated by non-realisation of the large-scale plans for an expansion of the renewable energy to support the green transition without building the relevant energy infrastructure. Nobody wants to invest in the expansion if how to dispose of the green energy and to which markets remain unclear. The relevant infrastructure is a necessary, although not sufficiently important, condition to succeed with the green transition process.

This issue exposes an integral inconsistent aspect of timing for the development of a new hydrogen market. A physical hydrogen infrastructure has to be established linking producers with buyers and consumers and thereby linking the markets.

***Box 3.1:** The need to regulate the future hydrogen market*

A RENEWABLE ENERGY FRAMEWORK
- Identification of relevant areas (offshore planning, government screening of areas for energy farms, local planning etc.)
- A process for allocation of areas (calls for tender, 'open door' and similar initiatives)
- Conditions for connecting to the electricity grid

A FRAMEWORK FOR THE ESTABLISHMENT OF ENERGY ISLANDS/HYDROGEN ISLANDS
- A special framework for renewable energy
- Decisions on the potential use of areas for other purposes than renewable energy

PRODUCTION OF HYDROGEN AND POWER-TO-X (PRODUCTION FACILITIES)
- Coordination with the production of renewable energy and consumption covered by the common electricity grid
- Availability of direct pipelines
- Access to and user conditions for the common electricity grid (discounts to large consumers, acceptance of potential disconnection etc.)

HYDROGEN INFRASTRUCTURE
- Tariffs
- Third party access

GENERAL ASPECTS
- Identification of an authority in charge of the hydrogen market/infrastructure and mandate
- The processing time and coordination of processes relative to deadline for final decision
- Definition of critical infrastructure and what this entails

The size, dimensions and siting of such an infrastructure must reflect the future demand, although in reality the demand will not be evident until an infrastructure allows deliveries and until hydrogen is produced. And hydrogen will not be produced until renewable energy for this is available and relevant market access is certain. This process requires many decisions to be made in several tracks whose timelines have not been aligned.

WHAT PLAYERS WILL BEST MANAGE THE VARIOUS RISKS PRESENTED BY THE INFRASTRUCTURE?

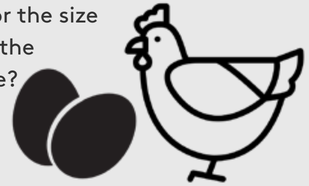
The best way to expand a market is to leave it to the players with the best insight into a specific area and the best possibilities for mitigating specific risk, i.e., leave the risk to the parts of the market where it makes sense. For example, the commercial players have the best know-how and the most detailed insight into the technological risks, development and options and they are, all things equal, the best to decide which forms of technology to apply, for instance in a call for tenders.

Furthermore, the commercial players have the most detailed insight into the market-related risks, for example through their market expertise, sales agreements and nose for various business models, and likewise the private parties who at micro level carry the risk of whether a financial activity generates profits or not.

At macro level, however, only governments, the EU and policymakers can carry the risk of the overall development of the market, i.e., whether the green hydrogen market will grow and not suffer collapse, primarily through political targets and requirements and through framework conditions.

THE INFRASTRUCTURE FOR AN EMERGING MARKET

What comes first: Establishing an infrastructure that will pave the way for the market or establishing a market whose demand will define the framework for the size and siting of the infrastructure?



Also as regards the need to shift the risk over time and between players, from the first uncertain period in a market with few players to a more mature market with multiple players, the Danish Government is in a position to influence this balance through regulatory measures (tariff structure etc.) and financial guarantees.

Pensions funds and other financial investors have the option to shift the risk involved in specific projects over time, but not the risk presented by the market as a whole. In addition to the technological risk, which for

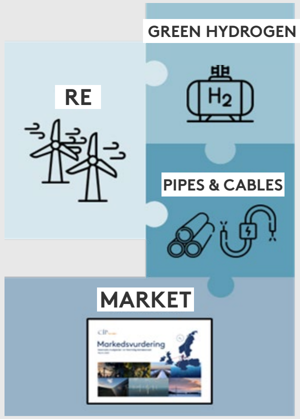
DILEMMA:

INCONSISTENT TIMING OF NEED FOR DECISIONS

Decisions have to be made concerning the establishment of an infrastructure and the capacity before knowledge is acquired about which forms of renewable energy sources can support hydrogen production, before knowledge is acquired about the demand of a hydrogen market, and before the producers know their transmission requirements.

Box 3.1: Production of hydrogen and Power-to-X products – an integrated value chain where one link's uncertainty reflects on the overall business case

A condition for the production of hydrogen is large quantities of green electricity from renewable energy sources and of water. A condition for supplying hydrogen is the existence of pipelines to the consumer markets. Consequently, for the production of hydrogen to exist access to renewable energy and to infrastructure is highly critical. Uncertainty, for example in the form of a non-transparent process and the timing of the supply of renewable energy, reflects directly on the business case for hydrogen production. In the same way, uncertainty as to whether a hydrogen infrastructure will come – if the interconnections are not private – when it comes and what it can offer in terms of capacity and storage options will also make its mark on whether producing hydrogen is profitable.



Since hydrogen will be transmitted in pipelines mainly, a restrictive factor will also be the size of the pipeline infrastructure, which in effect will set the framework for the potential demand for hydrogen. To this should be added the general uncertainty concerning the future green hydrogen market, which is in its early infancy, including the development of prices, the options available for a transition from grey to green hydrogen and the conditions for buyers and consumers.

As can be understood, an offshore wind farm delivering electricity to a known and mature electricity market with existing interconnections and buyers/consumers is an entirely different case in terms of economy and risks than if the same offshore wind farm will mainly be delivering electricity for the production of hydrogen and PtX products with yet unknown buyers/consumers, infrastructure etc. When excess renewable energy will not be used directly to cover the consumers' electricity consumption but instead as input for hydrogen and PtX production, this alters the risk profile for the establishment of the renewable energy source.

hydrogen is linked to electrolysis and the possibilities for using it for large-scale production and ramping up the overall capacity within a short time, using green electricity as input also carries a risk.

For hydrogen, operating costs are often more important than building costs, and in this context the price of green hydrogen is decisive due to its large share of the operating costs. Producing hydrogen requires large quantities of renewable energy at fair prices.

Through its approval of the tariffs, the Danish Government decides the size of the areas offered for production of renewable energy, the applicable terms and conditions, the approval processes and timing and also the potential transmission price. As part of its new, green industry policy in response to the US hydrogen production tax credit and electrolysis development, among others, the EU has been considering shorter processing times, which could reduce some of the risk and also ensure that more decisions are made in parallel.

For a common infrastructure, the risk of planning and the responsibility for coordination lies with the central authority. Accepting that the commercial parties join in the planning and co-funding of the infrastructure provides the best incentives to make use of knowledge from the market of relevant places of production and consumption, also internationally, and optimise the geographic location and the dimensions of the infrastructure. The many forms of uncertainties and risks of planning and building an infrastructure require a certain degree of flexibility and a staged process.

> In view of the uncertainty of the technology as well as the market development and regulatory possibilities, a future hydrogen market should preferably be governed by a relatively flexible and uncomplicated framework.

This is also the approach adopted by the EU, see Chapter 2.

POTENTIAL WAYS OF HANDLING AND MITIGATING RISKS

The electricity market in Denmark is now allowed to expand the infrastructure based on expected demand and not 'identified' demand in order to ensure that the capacity can meet the requirements for the future direct electrification, and the Danish TSO, Energinet, has been given the mandate to design, plan and build in advance through long-term development plans which are revised and approved by the Danish Parliament as they are presented.

> By the very nature of this issue, the hydrogen infrastructure should be structured according to the expected demand since the market is still in its early infancy although with the hydrogen infrastructure providing the required access to the market. For the common hydrogen grid, this could for example be made possible through long-term development plans, as known from the electricity grid.

When an infrastructure is built in advance, a risk is assumed regarding the future development of the market and with this the future use of the infrastructure. Part of this risk can be alleviated through binding commitments from existing market players about the future use by exploiting their insight into the market. This is an approach known from the gas market, for example, where market players are allowed to submit bids for their use of future capacity and commit themselves to a certain need for capacity over a period of time against a certain discount through an 'open season' procedure during the period prior to the planning of a new infrastructure. According to Copenhagen Economics (2023), this process was used in connection with the planning of the Baltic Pipe project, the expansion of hydrogen pipelines in Belgium and also for the LNG terminals in Germany, the Netherlands and Belgium, to name a few.

> In order to benefit the most from the knowledge possessed by the market players about the future hydrogen market, timing and quantities, it is proposed to call for offers for the capacity of the future hydrogen infrastructure during a certain period, 'open season', with players making preliminary commitments.

However, an early process where the players commit to a certain capacity before a final decision is made for the location and dimensions of the hydrogen structure can only take the producers that already exist or are in the process of being set up into consideration, which would be relatively few for an emerging market. For a common infrastructure, the Government can take future users, perhaps not even existing yet, into consideration and support the future competition by ensuring over-dimensions from the start compared to the capacity which the initial market players are able to commit to. Only the Government can assume this form of risk on behalf of future players.

> The Government has the option to assume the risk of providing an infrastructure with dimensions not only for the existing producers but also for future users which not yet exist today.

If the Danish Government assumes the initial risk of building a common hydrogen infrastructure, the Government also has the possibility of having its expenses repaid through future tariffs (see also section 3.5). These expenses can also be repaid with interest by including a reasonable required rate of return in the tariffs.

When the Government assumes a future risk, the Government also assumes the risk, however, that the market will not extend beyond the initial, limited start or collapses at some time. And with this, the future tariffs received from the transmitted quantities will not suffice to cover the costs of the hydrogen infrastructure ('stranded assets'). Since by far most of the green hydrogen produced in Denmark will go to our closest neighbours, the Government can seek to mitigate this risk through bilateral arrangements, for example for the international pipelines; just like Germany, the Netherlands and Belgium have all announced import requirements far in excess of the quantities Denmark will be able to produce through the hydrogen strategies of these countries (the CIP Foundation, March 2023).

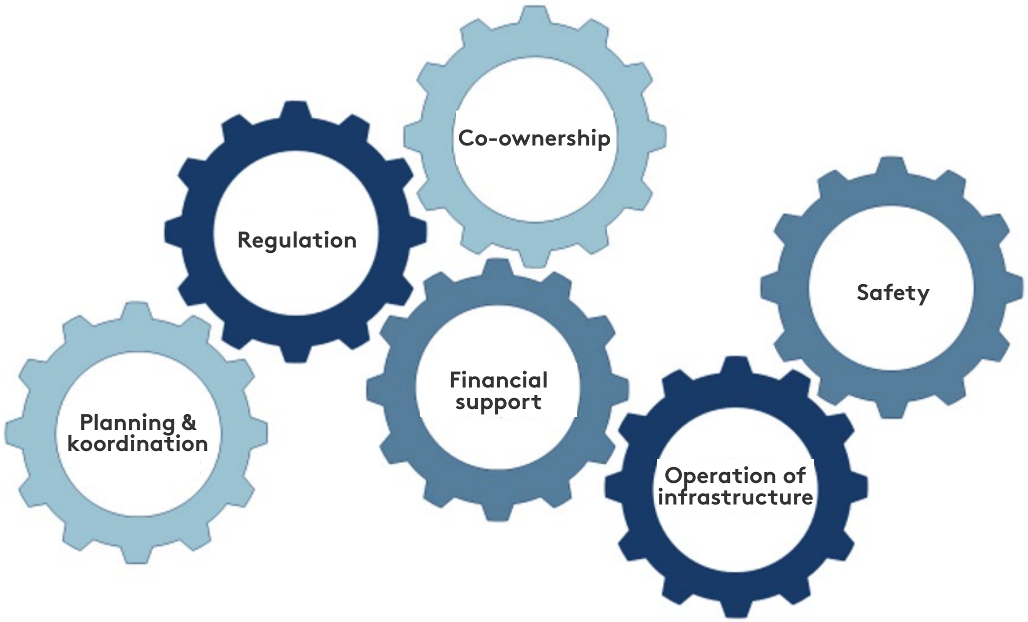
THE VALUE OF A TIMELY FRAMEWORK AND REGULATION

As the market matures, insight into the market evolves and more players emerge, the need for more specific regulation procedures grows. Although part of these regulations can be developed and refined as more insight is gained, the market developers also need to know the overall and long-term framework as early as possible.

The better the future spectrum of potential costs (and income) can be narrowed down, the more transparent is the business case. This speaks in favour of an approach involving an initial flexible framework and use of common minimum standards although with sufficient room for local variations, which also goes hand in hand with the EU's view on the future regulation.

> To begin with, the regulation of the hydrogen market could rely on principles, and a long-term framework could be announced so that the course is set, and the funding model is known while the details of the regulation will be developed over time within this framework.

***Figure 3.2:** Potential roles at national level in a future hydrogen market and the possibilities for reducing or transferring risk*



At the general level, the Government can help resolve part of the inconsistency associated with the timing and reduce the risk associated with the development of the market through early mapping of potential areas for renewable energy production; setting up rules, processes and time schedules for calls for tenders and contract awards; and ensuring planning processes.

Timely regulation and knowledge of the framework help lower the costs of building the facilities for more renewable energy, setting up new hydrogen production and adapting the need for an infrastructure[3]. This way the Government can exert a direct impact on the costs of the green transition; conversely, late and non-transparent regulation will have an immediate impact on the costs of setting up and producing hydrogen since the uncertainty concerning quantities and timing will be interpreted as a risk margin by the market players.

A non-transparent framework and waiting time during the processes, including approval processes, or extensions of deadlines will add to the risk assumed by private parties and will be included as direct additional costs for the project.

For the developers, transparent and timely planning and regulation (and the same for approval processes etc.) are competitive parameters and can play a part in providing Denmark with a first mover advantage in relation to the future Northern European hydrogen market.

3.3 The Government's role for the value chain?

The Government will typically play a major role as regards the infrastructure, especially if the infrastructure is important for the domestic supply and with shared elements. For electricity as well as hydrogen. The excess renewable energy will have to be exported either in the form of electricity or Power-to-X products, including green hydrogen. And so exporting energy based on Danish renewable resources is a political decision and this is where the future hydrogen market is an obvious route, see the Market Assessment of the CIP Foundation (March 2023). According to the Danish TSO, Energinet, an otherwise reinforced electricity grid in Denmark and in our neighbouring countries will not be able to consume all of the renewable energy produced using for example North Sea resources which is why the production of hydrogen will make it possible to fulfil the political expectations for the building of renewable energy capacity.

The Danish Government could take on many different roles in the process of building the future hydrogen infrastructure for the green hydrogen market. However, it is a question of balance. The deeper the Government is involved, the greater the loss of market dynamics, and the greater the risk of generating a form of action paralysis in the centralised coordination process.

The Government may take on various roles, all playing their part with regard to the infrastructure and all with the potential to reduce the risk for the market players or shift the risk over time in various ways. This does not mean that the Government has to take on all roles since several of them can also be managed by private players. As an example, the Government is the obvious party to structure and coordinate the common infrastructure but need not necessarily manage the funding part or the operation of the infrastructure.

One of the reasons why it is relevant for the Government to poke its nose into a future hydrogen market is that a large majority of the Danish politicians has set targets for the expansion of renewable energy which by far exceed Denmark's energy requirements.

3 For example, according to an evaluation made by Copenhagen Economics (2022b), early expansion of onshore wind and solar energy for the direct electrification alone can provide savings amounting to more than DKK 5 billion during the period up to 2030.

***Box 3.2:** Potential roles for the Danish Government in connection with an infrastructure*

Planning and coordination: Centralised planning and coordination of a common infrastructure is best undertaken by the Government, including decisions to be made concerning siting and dimensions. As regards the international pipelines to be built, the Government can also handle the dialogue with international parties, for example where the interconnection will be of a more joint nature.

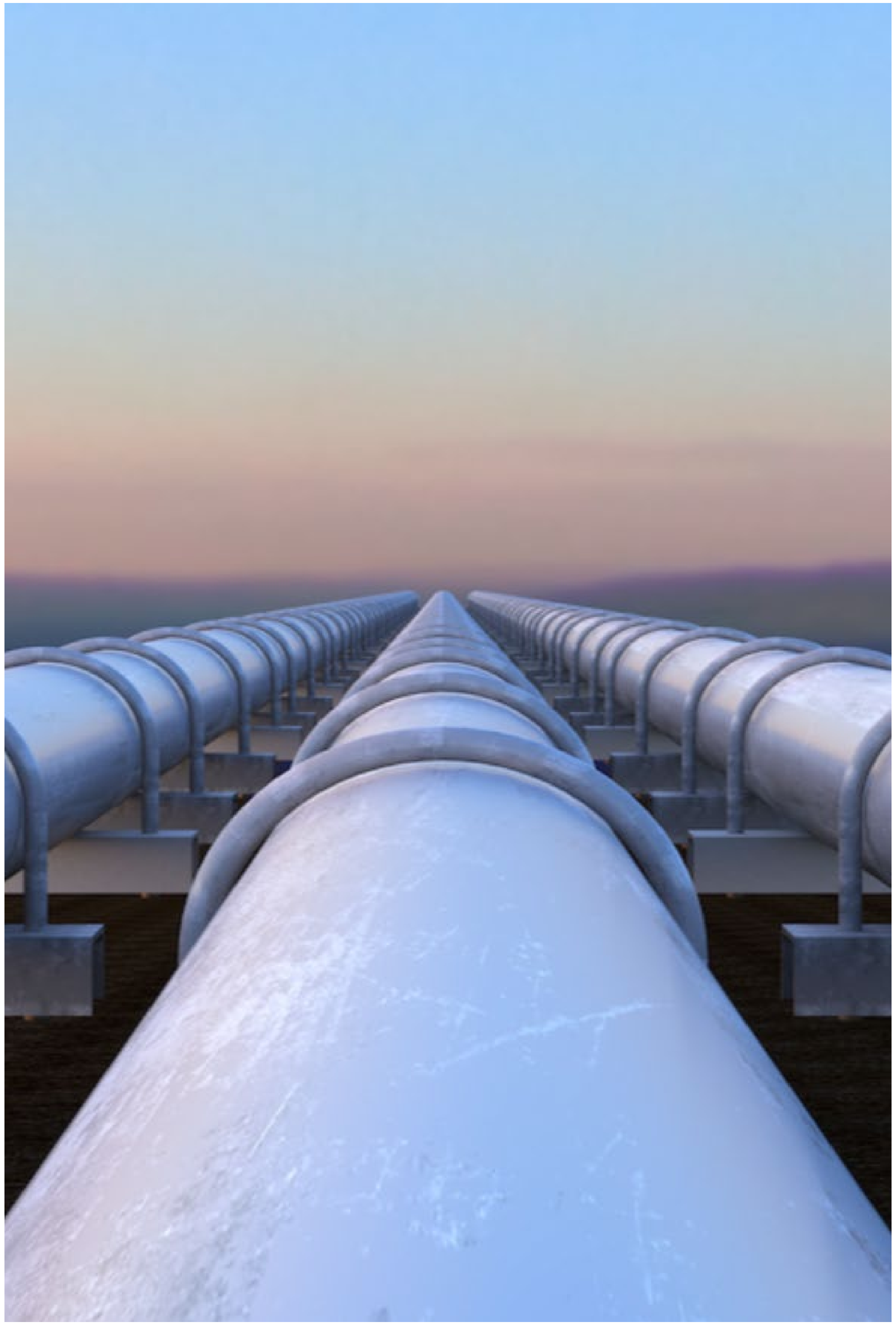
Regulating the framework: The Government is responsible for setting up regulation procedures and ensure compliance with the framework for access to and use of an infrastructure (connection, third party access) and likewise the government authority can also set the relevant prices for the use (tariffs).

Funding and support: The Government can co-fund an infrastructure, for example by accepting a higher risk during the initial stages of the emerging the market when the number of producers will still be insufficient to cover costs. This will shift some of the initial risk of developing the market from the developers to the Government, and over time from some of the first market players, when the risk is highest, to some of the future market players, when the insight into technology, development of the market etc. has deepened. If the Government's 'outlays' are not paid back later, they will count as government subsidies. The Government can also subsidise directly through support programmes and similar initiatives, although that strategy will count as public consumption. Given its access to relatively low-cost funding and its long time horizon, the Government has the option to shift the risk over time, which is relevant for a new market that supports national needs while at the same time satisfying political objectives (regarding renewable energy capacity). The financial market and for example pension funds could also accept a long-term risk and shift this risk over time, although not on behalf of an entire market and future consumers.

Co-ownership: The Government could become party to the production and transmission of hydrogen as co-owner together with commercial partners and with this accept a larger share of the initial risk, enable the construction of a wider network of pipelines and set up co-funding. See a separate section elsewhere which discusses the pros and cons of public co-ownership.

Operation of the infrastructure: This could also be undertaken by the Government or by an external operator subject to relevant regulation. This will include operation and maintenance and constant management of capacity allocation and pressurisation. The management of bottlenecks and scarcity must be coordinated between several possible interconnections, if there are multiple pipelines, and will have to relate to domestic consumption.

Security: With the blast of Nord Stream 2 and Russian mapping of offshore wind farms, cables, pipelines etc., which form part of the offshore infrastructure, the question of security crops up – whether Denmark's monitoring of the infrastructure is sufficient and if the level of security is appropriate. This is a job not only for the commercial players operating the facilities etc. but very much so also for the Government – especially where the infrastructure is of a more critical character for society. This issue is expected to form part of the future defence negotiations about how to spend the increased defence budget, among others.



3.4 Onshore and offshore hydrogen infrastructures serve different purposes

A range of different onshore hydrogen and PtX production facilities are expected to be built in Denmark, as can be seen from the market dialogue with the gas distributor Evida and the TSO Energinet (KPMG 2022) and the list produced by Hydrogen Denmark. They will differ in size, purpose and geographic location, scattered all over Denmark, based, among things, on the renewable energy sources they expect to consume, be they onshore wind or sun or nearshore wind.

An onshore hydrogen network interconnecting those who need it will be a type of shared network and support both domestic supply and exports once onshore international pipelines are installed. Further to this, the onshore hydrogen production will also play a balancing role in relation to the electricity grid, especially through its use of green electricity when this is in plenty supply and thereby help reduce the need for expansion and reinforcement of the electricity grid.

The typical role for the Government will be in the planning and construction processes of a common infrastructure and in ensuring the reliability of supply through the use of various forms of energy, see section 3.3. This also applies to the establishment of interconnectors or international pipelines to other countries where the Danish Government has typically taken care of the establishment through the Danish TSO, Energinet (electricity and gas (transmission)).

Offshore hydrogen production, for example on future energy islands, can be of large proportions based on large offshore wind farms far into the sea. The primary objective of this form of hydrogen production would be exports given the relatively modest demand for hydrogen in Denmark.

In that case, the relevant hydrogen infrastructure would be in the form of pipelines leading directly from the production site to the consumers (for example via a common interconnection/port infrastructure and then to the individual consumers).

> When designing the regulation, inspiration could be taken from the new Danish electricity regulation which allows direct lines without certain conditions.

All things equal, there will be fewer players for offshore hydrogen production if the scale and the capital requirements are far beyond that of onshore hydrogen production.

Since the hydrogen production should be expected to differ in various aspects, its purpose and requirements, the future regulation of the hydrogen market and the infrastructure must also take these aspects into consideration, no matter if the production takes place onshore or offshore.

When private players build direct pipelines – also when they in fact constitute international offshore interconnections – their dimensions match the expected requirements of the player concerned. Quite understandably, the business case of the commercial players does not take into consideration the potential need that other parties might have to connect to the infrastructure at some point in the future. Although the initial character of the need is more that of a direct pipeline from a production site, for example an energy and/or hydrogen island, and consequently built by a private player and with private funding, new players may present a need to connect to the original pipeline based on new areas for renewable energy.

> The need for regulation of a common hydrogen infrastructure differs as regards the need for regulation of private, commercial pipelines and with this most likely also the need for regulation of an onshore or offshore hydrogen production, respectively.

> One aspect to consider is whether the Government should have the option to ensure over-dimensions of major offshore pipelines that connect to destinations of consumption in order to allow for potential access by future competitors and a growing use over time.

Most likely, small-scale offshore hydrogen producers, for example those relying on production from platforms or from a single wind turbine, will not have the capital required to build their own hydrogen pipelines covering long distances and could benefit from connecting to export pipelines owned by others from offshore facilities. This structure is known from the oil and gas market where several small-scale operators can connect to central pipelines against a fee (third party access).

Even if a private player would want to set up a common infrastructure together with operators among the local competition, potential future players cannot be allowed for at the early stages of the market.

Only the Government can take on the role involved in taking into consideration future market expansions and supporting future competition. And the Government has the insight into where the future competition might arise since the Government plans and invites tenders to bid for offshore areas dedicated to renewable energy production and with this indirectly also to offshore hydrogen production.

3.5. Tariffs are payment for use of the infrastructure

Tariffs are a form of user payment which is intended to cover the costs of using a common infrastructure, including its construction, day-to-day operation and a return in the event there are multiple users. Tariffs can be set for connection, transmission (network tariff) and for system services, which include storage options associated with the infrastructure.

Establishing a hydrogen infrastructure requires considerable capital with a sizeable investment up front. If the costs were to be covered by the first, relatively few users, the cost of using the infrastructure per transmitted quantity of hydrogen would be prohibitively high. At the same time, these are capital investments with a relatively long technically useful life.

> The price of using an infrastructure should be set according to the long-term costs and reflect its expected useful life.

Taking this approach, some of the costs of using the infrastructure are in practice shifted from the first initial period, when the transmitted quantities are not all that large and when the market is still in its early infancy, to a later time when larger quantities are transmitted and when the market is more mature and less risky, as illustrated by Figure 3.3.a. This figure shows how the costs of using the infrastructure immediately move downwards as the transmitted quantities rise, only to go upwards again as the pressure rises and until full capacity has been reached.

A hydrogen infrastructure with relatively few and major consumers would, all things equal, be more sensitive to the behaviour of individual users and decisions about input and output than known from other types of energy infrastructure, such as the gas grid, according to Copenhagen Economics (2022a). Costs will also have to be divided between relatively few players. Consequently, the owner of the infrastructure would benefit from ensuring as much commitment as possible from the users, for example through an 'open season' approach, where dialogue takes place with the market in the run-up to the construction phase to get the users to commit to a certain use of the capacity. These commitments are not as such legally binding and can be derogated from according to certain conditions as agreed. Such commitments are a way of ensuring a certain use of the infrastructure in the initial phase when the uncertainty is highest.

In order to ensure commitment to as much capacity as possible up front there must be some sort of financial incentive. Otherwise, the market players could potentially have their own individual free rides and await the establishment of the market and more in-depth insight into its development. If the tariffs are set relatively low to begin with (a 'discount' to first users), this might ensure more extensive commitment to use the infrastructure.

With the staged structure over time where the price of using the infrastructure gradually increases as the quantities grow – the tariff structure illustrated in Figure 3.3.b provides financial incentives which reflect the market-related risk which is high especially at theonset when the market is under development and then declines as more users and more buyers/consumers join the process. An initial discount on transmission of green hydrogen is also in agreement with the principles proposed by the EU, see Chapter 2.

3.6. Ownership of hydrogen infrastructure

For an infrastructure of a common nature there are several possible ownership models. By tradition, in Denmark the ownership of infrastructures varies. State-owned companies are in charge of planning, construction and operation of the electricity grid and the natural gas network, whereas initially the offshore oil and gas infrastructures were on private hands and for some sections still are. Since 2005,[4] the public sector has enjoyed a 20% co-ownership of the production of oil and gas via Nordsøfonden (the Danish State Subsurface Resource Company). State co-ownership is typically entered out of consideration to society, for example to contribute to the reliability of supply, and lately CCS (capture and storage of CO2 in the North Sea) out of consideration to the political climate targets for Denmark.

Recently, direct pipelines for the supply of electricity were allowed; these are point-to-point interconnections between production facilities and consumption facilities funded and owned by commercial players. This option has been introduced to support the future production of hydrogen and Power-to-X products, among others.

Figure 3.3.a: *Illustration of long-term, cost-based tariffs*

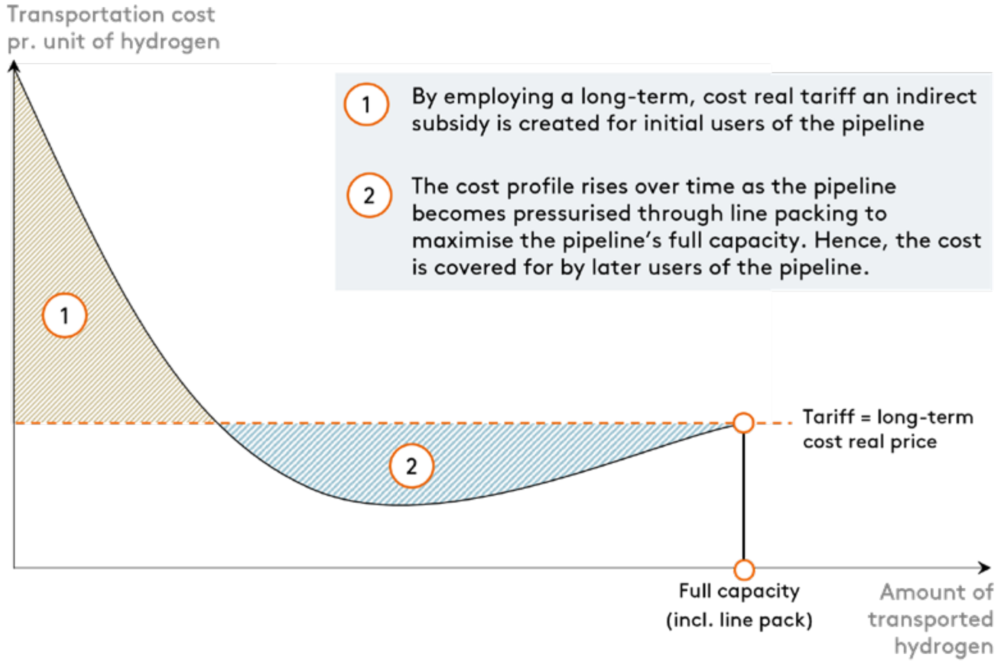
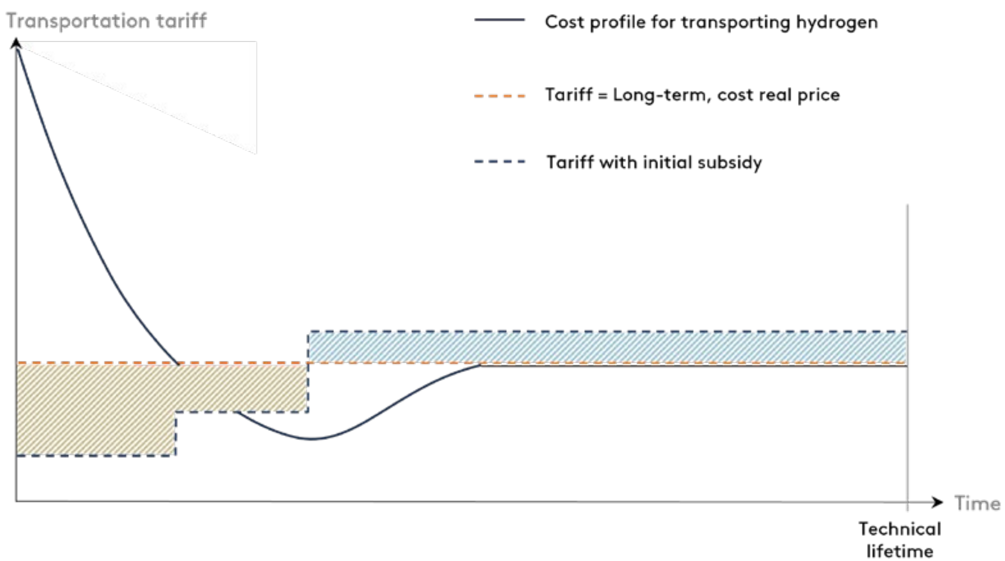


Figure 3.3.b: *Staged tariffs with initial discount*



4 2012, as far as the exclusive right granted to DUC is concerned.

As a result of this, by experience there have been different and several instances of mixed forms of ownership. Decisions concerning the form of ownership have also been founded on the question of whether the infrastructure was found to be of a critical nature, see Box 3.3.

For a common hydrogen infrastructure, the Government needs to be involved in the planning, designing and initial provision of security on behalf of the future market players, as discussed earlier. Danish production of hydrogen is not as much a question of domestic reliability of supply, it is more a question of the role that hydrogen production would play for the balance of the electricity grid and to make use of the large quantities of renewable energy without having to expand the electricity grid notably. This factor lends hydrogen a socioeconomic role in Denmark.

In May 2023, Danish politicians adopted an in-principle agreement according to which the state-owned operators Energinet (TSO) and Evida (gas distributor) are to plan and build the hydrogen infrastructure in Denmark. By exception, direct pipelines in private ownership can be accepted if they are not part of a coherent hydrogen structure and provided neither Energinet nor Evida see ownership and operation of the section concerned as valuable assets[5].

The infrastructure expansion proposed by the CIP Foundation will require considerable investments and has the potential as a whole to become the largest construction project ever in Denmark. Since most of the hydrogen will be exported and this is very much a commercial issue, production-wise, these two elements could speak in favour of a combined ownership and funding set-up for this infrastructure.

Table 3.1: *Ownership options for the infrastructure and the production of energy or for services for the infrastructure*

Type	Infrastructure	Production	Comments
Electricity	The State (Energinet)	Private actors	Previously the production of renewable energy was subsidised (guaranteed prices) but recently the Thor offshore wind farm was erected without public subsidies.
Oil/gas (offshore)	Mixed*	Mixed	The state-owned company Nordsøfonden has a 20% ownership of the North Sea concessions and is part of the entire process from the investment stage to allocation of profits (to the State)
Biogas	The State (Energinet for transmission and Evida for distribution)	Private actors	Subsidised up to a guaranteed price for a certain period of time.
The mobile phone network	Private actors	Private players (telecommunications)	The telecommunications network was originally owned by the State but has transitioned into private ownership.
Broadband	Private actors	Private players (telecommunications)	Market-based rollout, with some sections subsidised by a broadband programme.
NEW: CCS/CCUS with transmission of CO2e from capture to storage or utilisation	Mixed	Mixed	Nordsøfonden is involved in all licences to store CO2e in the underground and has the mandate to participate all through the CCS value chain up to 20% (CCS - Carbon, Capture and Storage; CCUS - Carbon Capture, Storage and Utilisation). Danish subsidies to CCS (DKK 10 billion
NEW: Hydrogen	The State (Energinet and Evida)**	Private actors	DKK 1.25 billion in Danish subsidies for promotion of hydrogen production.

Notes: * The first offshore oil pipelines were installed by private operators and the State later obtained an ownership share through the Danish Underground Consortium (DUC) via Nordsøfonden. Ørsted still today owns and operates three upstream pipelines for oil and gas. ** According to the political agreement of 23 May 2023, the general decision is that Energinet and Evida are to own and operate the hydrogen infrastructure in Denmark and the interconnections to other countries.

A mixed ownership structure should be considered for the future hydrogen infrastructure in order to introduce a larger share of private capital for the construction.

5 The Danish Government (2023): Mulighed for etablering af brintinfrastruktur. 1. Delaftale: Ejerskab og drift af fremtidens danske, rørbundne brintinfrastruktur, principaftale af 22. maj. [Part 1 of an in-principle agreement concerning the possibility of establishing a hydrogen infrastructure of 22 May]

***Box 3.3:** Critical infrastructure – a concept under development*

The concept 'critical infrastructure' is not well-defined as such but can be understood as 'facilities, systems, processes, networks, technologies, assets and services that are necessary to retain or restore functions of importance to society.'

The scope of this concept has changed over time and in wavelike patterns to the tune of for example privatisation trends. It has also, however, had a tendency to change with geopolitical changes and changing threats, such as health crises like the COVID-19 pandemic when PPE (personal protective equipment) became critical infrastructure, and with technological advances where cyber security now plays another role than it used to do.

The Government has typically associated critical infrastructure with public ownership, co-ownership with controlling influence or commercial Danish ownership, according to Copenhagen Economics, as is known from for example Copenhagen Airports or the telecommunications network (TDC). Other examples of critical infrastructure are the gas grid, the payment infrastructure in the financial sector, monitoring of ship traffic.

In 2021, the Danish Parliament adopted the Investment Screening Act with the intention to ensure that foreign investors have to apply for permission (with the Danish Business Agency) to engage in foreign direct investments (FDI) in particularly sensitive sectors (defence, dual-use, IT security, critical infrastructure and critical technology).

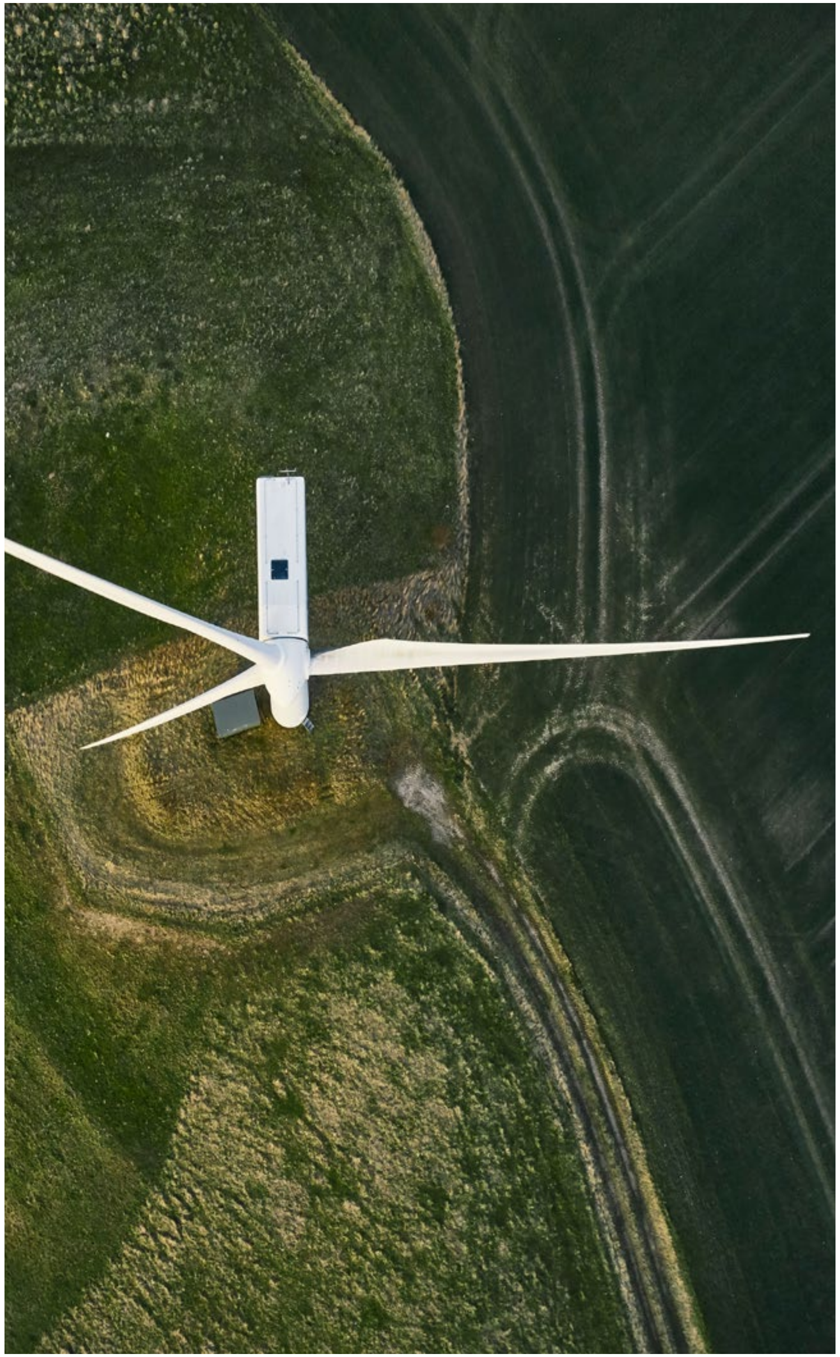
The EU has decided that operators of critical infrastructure will be appointed in future. In the understanding of the European Commission, critical infrastructure is any system that is vital to perform important economic and social functions: healthcare, food, security, transport, energy, information systems, financial services etc.

When it comes to very large suppliers of energy, for example future energy islands, these are sometimes referred to as 'supercritical infrastructure' (for example by the Berlingske newspaper) much like institutions of importance to the system, as is known from the financial sector. Interruptions in the supply from energy islands will due to the scale have an impact on and destabilise Denmark's overall electricity supply with the potential risk of black-outs due to failure to balance the production and consumption of electricity. As an example, with its production of 3-4 GW electricity by 2033, the future energy island in the North Sea will cover about half of Denmark's electricity consumption, according to the Danish Energy Agency.

For this type of infrastructure, it could be relevant with extraordinary monitoring and to establish more supply lines, electric cables as well as hydrogen pipelines, in order to ensure a more reliable supply in the event of an interruption. This form of over-dimensioning, with redundant lines compared with the immediate transmission requirement, provides added flexibility and security in the event of a breakdown somewhere along the supply lines and should be weighed against the additional cost.

The construction of a hydrogen infrastructure and the production of hydrogen and renewable energy linked to this could have the character of critical infrastructure; although this does not necessarily imply that the ownership should be public. However, clear rules should be laid down for how to protect and monitor the installations.

Sources: Based on input from Copenhagen Economics (2022a), kritiskinfrastruktur.dk, the Berlingske newspaper of 30 April 2023 and the Danish Business Authority.



***Box 3.4:** A common hydrogen infrastructure – Public-Private Partnership (PPP) like Sund og Bælt, with private capital as supplement?*

In order to combine the need for public involvement and the possibility to hedge markets and shift the risk over time through funding and market insight provided by private players, a public private partnership can be set up for a future common hydrogen infrastructure. This will combine the planning of common sections with a state guarantee for the initial investment and with private capital as a supplement.

In a state guarantee model, the Danish State will issue a guarantee for the loans needed to set up the hydrogen infrastructure via an infrastructure operator. If the hydrogen infrastructure crosses borders, both countries can issue a joint and several guarantee for the loans as is the case for the Øresund Bridge. The State issues a guarantee for the loans against a guarantee commission, which thanks to Denmark's good credit rating as a nation gives access to favourable lending conditions. Private investors with a long time horizon, for example pension funds, will be given the option to supplement the funding with private capital. Private investors are not allowed to also be part of the value chain, for example as hydrogen producers, see the proposed EU principle about unbundling. If the hydrogen infrastructure is found to be a critical infrastructure, the Government can have a controlling influence on the company.

User payment (tariffs) will be charged, and interests and instalments will be paid on the loans – after payment of operating and maintenance expenses and return to the owners.

The state guarantee model is known from Sund & Bælt Holding, among others, the parent company of for example A/S Femern, A/S Storebælt and A/S Øresund, all infrastructure projects split into separate companies. In the same way, a holding company can be set up with subsidiaries for the individual stages of the implementation of the hydrogen infrastructure.

Combining public and private capital is relevant because hydrogen will be produced with commercial export in mind and because the investors can be secured a return from a model of this type through the tariffs to be paid by the companies using the hydrogen infrastructure.

3.7. Possible principles for regulation of the future hydrogen infrastructure

The future green hydrogen market is still in its early infancy and requires a relevant regulatory set-up of considerable flexibility for the initial period when the uncertainty will be most notable. Also required is that the Government helps mitigate the risk in the start-up phase, to be repaid later, supplemented by private capital.

Within a relatively short period of time, decisions have to be reached concerning the future hydrogen infrastructure and for this purpose a responsible planning authority (TSO) for the common sections and for coordination with other countries has to be appointed. With costs of this scale for the establishment of a hydrogen infrastructure and an export focus of this magnitude, much of this has to be coordinated with other countries in order to benefit from economies of scale and joint funding, to the extent possible.

There are fundamental differences between onshore hydrogen production, where balance is required between the electricity grid and the supply needed to cover both domestic consumption and the production of PtX products for exports, and offshore hydrogen production on energy islands and similar constructions, which can deliver directly to the export markets and operate large-scale production which exploit their close vicinity to large sources of renewable energy. The regulation, forms of ownership and contributions to society must also be able to allow for these differences, also the risk profile.

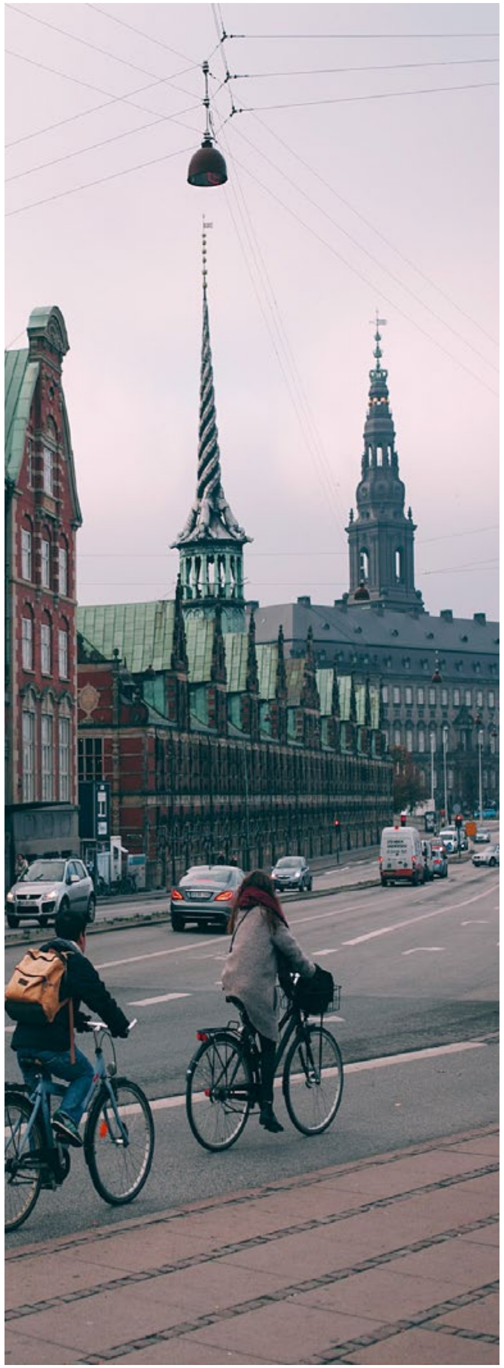


***Table 3.4:** Overview of relevant the principles and framework for a future hydrogen market*

Point of departure	Implications
Since …	*What is needed may be…*
• The market for green hydrogen is in its early infancy • Energy export is determined at the political level where capacity targets have been set for renewable energy far in excess of Denmark's requirements • The export has to some extent be in the form of hydrogen as the energy surplus exceeds the capacity of the electricity grids • The risk of collapse of the market as a whole cannot be covered by market players • The Government offers offshore areas for renewable energy and decides the associated process for them • Marked front-loaded risk profile for the infrastructure funding and a condition for start-up of the market is that the risk is reshifted over time between players	• **State involvement** in the hydrogen infrastructure through the participation of public authorities and an infrastructure operator: • Timely regulation of the future hydrogen market and the relevant transmission • Planning and dimensioning for the future • State guarantee for the future use of a common infrastructure (in addition to the current players), potentially supplemented by private capital • Monitoring and protection
• One or more risks in the value chain **reflect on** the viability elsewhere in the chain	• **Coverage of the costs of the infrastructure from a long-term perspective** through cost-based tariffs over time, which reflects the useful life of the asset and provide a return to the owners • **Transparent rules** for calls for tenders for renewable energy and the relevant deadlines and approval processes
• The **timing is inconsistent** for the various market decisions affected by processes organised at state level • **The risks have to be mitigated** where possible through timely regulation and transparent procedures • **Early announcement of the market's needs** is required	• **Staged regulation** • Flexibility and minimum rules and standards to begin with • Early announcement of frameworks with a long-term perspective for later, more specific regulation • Discount on tariffs in the event of early commitment to a need for transmission through the infrastructure by means of open season announcement
• Most of the Danish hydrogen production will be **exported**	• **International coordination of international pipelines** where especially offshore hydrogen production is to be connected to the infrastructure of other countries to benefit from economies of scale and reduce the costs of market access, to the extent possible • The market buying the hydrogen must bear its share of the risk/funding of the hydrogen infrastructure through common, international pipelines
• Several market players have announced plans to set up **onshore hydrogen production** which can provide enough hydrogen to meet both Danish requirements and exports, whereas **offshore hydrogen production** would be reserved for fewer player and with an immediate intention to export	• The option for **direct pipelines** • **Various needs for the regulation** of a common infrastructure and direct lines

A long-term plan for a Danish hydrogen infrastructure

Chapter 4

Long-term plans for renewable energy and construction of an infrastructure in Denmark are of major importance to the maturing and development of the market for green hydrogen. Transparent future plans will provide developers, investors and other market players with certainty and reduce the need for funding to the benefit of the entire society.

4.1. Plans expanding the production of renewable energy

A prerequisite for building a hydrogen market is a massive expansion of the production of renewable energy.

Today, Denmark has installed 2.3 GW offshore wind. The ambition is to build up to the full potential of the North Sea during the period up to 2050. To this should be added the construction projects in the Baltic Sea and the Kattegat, the construction of energy islands, Power-to-X (PtX) facilities and hydrogen pipelines. Let alone during the period leading up to 2030, renewable energy totalling 9 GW, an energy island and a number of open-door projects are set to be established.

It poses a challenge that the construction of new wind energy facilities has been on stand-by for a period and that the construction of new wind turbines and photovoltaic installations is nowhere near fulfilment of Denmark's 2030 target. An analysis produced by the Danish Energy Agency shows that not a single wind turbine will be erected on land in 2023 and 2024 and that the expansion of offshore wind is still progressing at a slow pace. With this in mind it is essential that the Government's ambitions will be realised as presented at a green energy summit at the Danish Prime Minister's official residence in April 2023.

Large-scale offshore wind capacity is vital to the profitability of large-scale hydrogen production. Reserving offshore areas twice the size of those reserved today for offshore wind turbines, as the Government is proposing, is a step in the right direction. Especially if these areas are located close to the international buyers and consumers, an example is Dogger Bank. The same applies to the possibilities for overplanting which increases the capacity by two thirds for a given area[1]. This is a cost-effective way of increasing the offshore wind capacity and is already taking place in Germany. Together with a larger, dedicated offshore area, this generates a significant increase of the renewable energy potential and with this the profitability of a future hydrogen infrastructure.

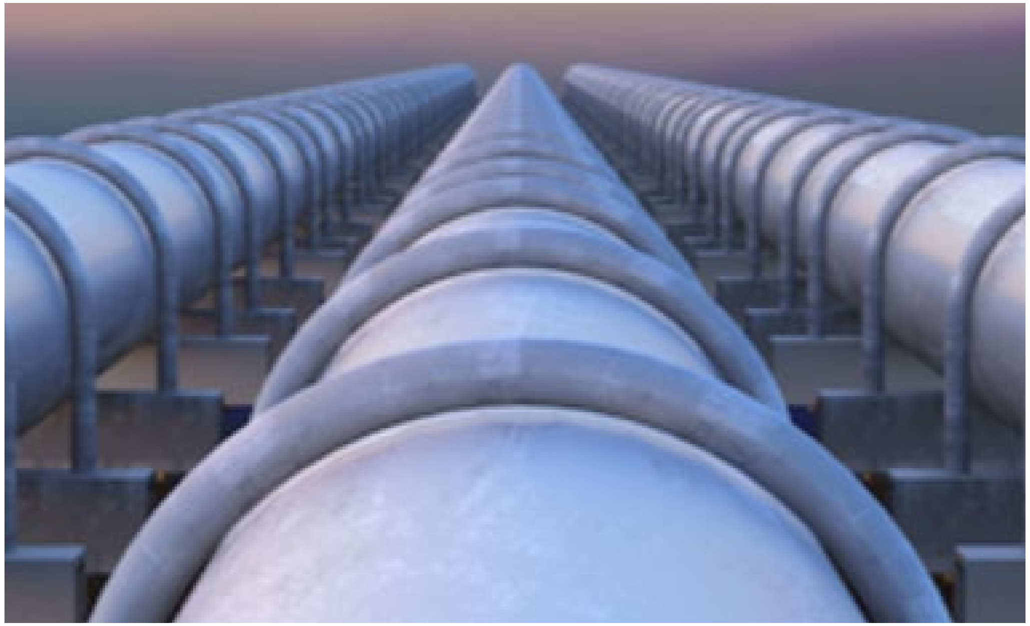
4.2 Danish hydrogen projects ask for plans with a long-term perspective

At the most recent market dialogue session with Danish hydrogen projects, the question that was most frequently asked was the siting of a future hydrogen infrastructure. More than 85% of all Danish hydrogen projects state that the lack of knowledge of a future hydrogen infrastructure is a serious impediment to the realisation of the projects and thereby the expected hydrogen production[2].

Many Danish projects expect having to make a final decision concerning their funding in 2023 or 2024 and here the plans for a future hydrogen infrastructure play a key role. The infrastructure is the necessary gateway and channel that will secure sales to the German market where there is a demand for the hydrogen.

A relatively precise siting of the future hydrogen infrastructure is of great significance to the operational as well as commercial aspects of the projects, also from a long-term perspective. Consequently, together with knowledge about the future framework conditions a plan for the future hydrogen infrastructure will create certainty about the funding of the projects.

Uncertainty concerning the future plans for building a hydrogen infrastructure and for the future framework conditions add to the risk and this again either results in added funding costs or postpones otherwise profitable investments in hydrogen production. For these reasons the Government plays an important role in the development of a market for green hydrogen with early announcements and a transparent and known framework for the long-term investments.



1 The Danish Government (2023b)
2 KPMG 2022

4.3 Collaborating with non-Danish hydrogen authorities is critical

As already mentioned, Denmark's closest neighbours need to import large quantities of green hydrogen, and Denmark has the potential to become a large-scale exporter of green hydrogen since the country will become self-sufficient in green electricity and green hydrogen at an early stage and has large wind potential, especially in the North Sea.

This export potential can be realised provided a hydrogen pipeline infrastructure with international interconnections and with the capacity to handle the large quantities expected is established and provided the Danish hydrogen authorities quickly set up collaboration with the hydrogen authorities in the countries that Denmark expects to export to – primarily Germany, the Netherlands and Belgium. The infrastructure with its international interconnections defines the export potential, since this is the gateway to the market. Since hydrogen produced in Denmark could potentially come to take up a large share of the overall hydrogen market in these three countries, this would also have major implications for the hydrogen infrastructure to be built outside of Danish waters.

For these reasons it is essential to integrate a Danish hydrogen infrastructure in the plans of Denmark's neighbouring countries from the start and to provide a common understanding of the dimensions of the infrastructure to ensure that it has the capacity required to manage the expanded production capacity expected in the period up to 2050.

Bilateral dialogues are already taking place with the German hydrogen authority, Gasunie, about certain hydrogen pipelines. Further dialogue is needed, however, between the authority responsible for the hydrogen network in Denmark, i.e., the Danish TSO, Energinet, and relevant authorities and players in the other countries to identify the possibilities and the most efficient way to transmit the hydrogen to the customers. A process of this type also has to include private players who are to be part of an open season procedure and who can contribute to the design of a common market and to the definition of the interfaces between private, public and third party pipelines.

As already mentioned, the European Hydrogen Backbone is a joint initiative involving a number of energy infrastructure operators who all want to accelerate the development of the hydrogen market in Europe by defining the hydrogen infrastructure. Denmark is part of this initiative, and this would be the obvious forum to make enquiries if a Danish hydrogen infrastructure is to be integrated with the plans of Denmark's neighbouring countries.

4.4. First mover advantages of early and explicit announcements about the infrastructure

The production side of a future hydrogen economy will most likely consist of a number of networks counting a range of different players focused on geographic locations, where for example renewable energy, electrolysis and district heating production can be coordinated and positioned alongside each other. The development of these networks will to a high degree be dictated by the framework conditions and the infrastructure which will have an impact on development options and the willingness to invest. The countries which first set a sound, well-defined and long-term framework for the future hydrogen production will give their domestic businesses a head start.

An early and focused announcement of the infrastructure plans and the priorities will create the basis for a commercial development of the Danish hydrogen economy without assuming higher risks than necessary.

Investors will be risking considerably less if the plans for a future infrastructure are known. This will reduce the costs of funding renewable energy projects and with this the costs of the green transition[3]. Wavering decision-making powers and unfocused plans will cause uncertainties for the hydrogen producers, whereas the reverse will generate an advantage and the possibility to become part of the hydrogen market of the future.

If Denmark is to contribute to Europe's green transition, a hydrogen infrastructure will be required. The sooner the plans and the framework are announced, the more Denmark will benefit. If Denmark is not at the leading edge, the country is at risk of being overtaken by its neighbours. And with good reason. Because in addition to the size of the market, the development of expertise and know-how will be very valuable for whoever takes the lead. For Denmark, an investment in a hydrogen infrastructure can generate a socioeconomic benefit twice the size of the investment[4]. For this to happen, the country has to take the lead.

The reason for this is that timely expansion of Denmark's infrastructure will give Danish hydrogen producers an opportunity to establish themselves at an early stage, and this will generate an ecosystem with a value chain consisting of multiple players – just like the wind industry has been a success for Denmark. Plans with a long-term perspective and clear framework conditions will provide Danish enterprises with experience and learning they can apply at global level, and which can be used to enhance Denmark's position of strength and the country's potential to develop green solutions in the rest of the world.

3 Copenhagen Economics for the CIP Foundation, 2022
4 https://energiwatch.dk/Energinyt/Cleantech/article14430396.ece

PART 2

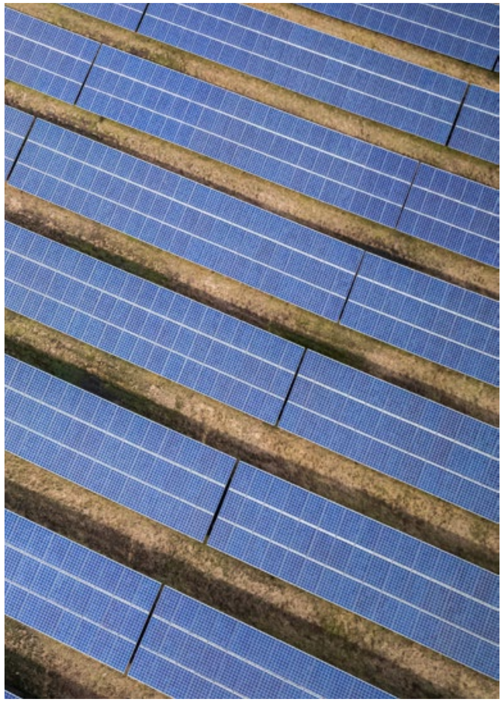
How to develop the infrastructure?

Design criteria

Chapter 5

5.1 Market conditions

Together with the production options and the renewable energy potential, the infrastructure plan will be based on the future demand for green hydrogen and determine the start and end points of the infrastructure to some extent. See Chapter 2 for a discussion of the market and export potential. To this should be added a number of more specific market conditions that have governed the expansion process.



***Box 5.1:** The hydrogen market will be large but sensitive to transmission costs and state subsidies*

Market conditions

The hydrogen market will be of a regional character since hydrogen for the most part will be transmitted in pipes out of consideration to the transmission process and costs.

Denmark will become self-sufficient in green electricity in 2027 and in green hydrogen before 2030 (the Danish Energy Agency, 2023). With this in mind, a hydrogen infrastructure is to support large-scale exports of hydrogen.

The price of green hydrogen depends on the price of renewable energy, the electrolysis capacity and transmission costs. Denmark enjoys cost-benefits of between 5% and 10% in the North Sea compared with other North Sea countries (Brinckmann, 2023). Consequently, it is assumed that Denmark will exploit the full potential for renewable energy in the North Sea.

The production from Danish sites could potentially result in production of 200 TWh hydrogen annually (the CIP Foundation, 2023). In view of this, the dimensions of the hydrogen infrastructure will allow a transmission of minimum 200 TWh a year.

The market for hydrogen is immature and will be affected by state subsidy schemes, such as the IRA (the US Inflation Reduction Act). It is assumed that the EU comes up with a response to the US subsidy schemes for hydrogen and Power-to-X (PtX) prompted by the EU's targets for an own production (the CIP Foundation, 2023).

Germany, the Netherlands and Belgium will become large-scale importers of green hydrogen and are obvious export markets for Denmark. The demand of these countries will total ≈215 TWh in 2030 and ≈500 TWh in 2050 (the CIP Foundation, 2023). Consequently, the hydrogen infrastructure is designed to be able to interconnect these markets.

The synergies between producing electricity and producing hydrogen can be considerable, and producers may be interested in switching between the production of electricity and the production of hydrogen, depending on the demand and the energy prices. Consequently, the hydrogen infrastructure is located close to relevant electricity infrastructure, and bothhydrogen and electricity cables have been installed from the hydrogen producing energy islands.

5.2 Political agreements and bilateral public authority arrangements

The hydrogen infrastructure is designed to manage the quantities resulting from the political ambitions set out in the Esbjerg Declaration and the Marienborg Declaration. In addition to this, the Government has set 4-6 GW electrolysis by 2030 as the target in its Power-to-X strategy. To this should be added a number of bilateral agreements, such as the newly signed Letter of Intent between Denmark and Germany concerning an interconnecting hydrogen pipeline, see Box 5.2.

Box 5.2: *The CIP Foundation's expansion plan supports political agreements and declarations*

Political agreements and declarations

Renewable energy:

- The Esbjerg Declaration (2022) and the Marienborg Declaration (2022)
- Climate agreement concerning green electricity and heating (2022)
- Green action: Fulfilment of the climate targets and accelerated expansion of renewable energy (2023)
- The Ostend Declaration: Targets of 120 GW offshore wind by 2030 and 300 GW by 2050 (2023)

Electrification:

- Electrification strategy: An efficient and forward-looking electricity infrastructure to support the green transition and the electrification (2021)

Power-to-X:

- PtX strategy: Developing and promoting hydrogen and green fuels, including the target of 4-6 GW electrolysis by 2030 (2022)
- The Ostend Declaration: Target of 30 GW electrolysis in the North Sea by 2030

Energy islands:

- Climate agreement for energy and industry etc. concerning the establishment of energy islands in Denmark, among others (2020)
- Addendum concerning the Bornholm Energy Island (2022)

Bilateral agreements:

- Agreements between Denmark and Germany, the Netherlands and Belgium, respectively, concerning Denmark's energy island in the North Sea and the Bornholm Energy Island for the delivery of electricity
- Bilateral agreement between the Danish and the German Governments to facilitate an onshore hydrogen pipeline from Denmark to Germany

5.3 Technical aspects

Furthermore, a range of technical aspects are important for the location and dimensioning of the hydrogen infrastructure. These technicalities concern, among others, the most appropriate form of transmission of the hydrogen, ways to store the hydrogen and the possibilities available for use of existing gas pipelines. The technical factors are discussed below.

Box 5.3: Pipelines are the cheapest way to transmit hydrogen

TECHNICAL FACTORS

Transmission: Transmitting electricity in cables is far more costly compared with transmitting hydrogen in pipelines – up to ten times as much for long distances. There are several reasons for this, for one that the requirements for the electrical cables increase with the distance; and for another that the price of these so-called HVDC cables is very high. To this should be added a considerable loss of energy and the need for transformation (Brinckmann, 2023). Consequently, the proposed hydrogen infrastructure encourages hydrogen production close to the renewable energy source.

Balancing: With hydrogen production, balancing the electricity grid can take place at times with high production of renewable energy (Brinckmann, 2023). Especially the location of the onshore part of the hydrogen infrastructure takes balancing into account.

Storage: The most appropriate and cost-effective way of storing hydrogen is in dedicated hydrogen pipelines (Brinckmann (2023) and DNV (2023)). Consequently, the very pipelines should be seen as a storage option, especially at the beginning when the production is small. Later, when the production grows, the pipeline can be pressurised to increase its storage capacity.

Storage in caverns: The caverns at Lille Torup can be used as a hydrogen storage facility (350 GWh) and for balancing (COWI, 2023).

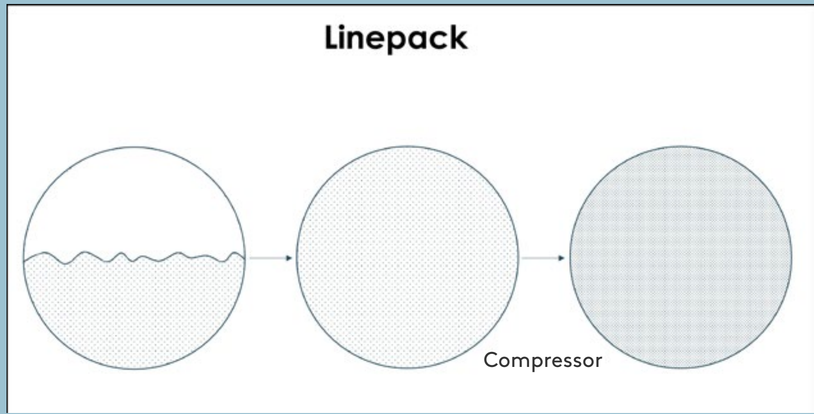
Reutilisation of gas pipes: Gas pipes can be retrofitted and then used to transmit hydrogen – but only to a limited extent for storage. For several years to come, most of the gas pipelines in Denmark will be used to transmit biogas (Brinckmann, 2023). Consequently, the analysis relies on a concept with a future hydrogen infrastructure consisting of newly installed hydrogen pipes that can also provide an efficient storage facility.

Cracking of PtX into hydrogen is not expected to have an impact on a Nordic hydrogen market (IEA (2019) and Copenhagen Economics (2022b)).

Box 5.4: The infrastructure pipelines could also serve as a storage facility

CAPACITY AND LINE PACKING

Hydrogen pipelines can be used as a flexible storage facility by hydrogen producers. In essence, the capacity of a hydrogen infrastructure is determined by the size, pressure and length of the pipe. During its initial stages, the market is expected not to make full use of the capacity, and as the market matures and the use of the capacity rises, the system can be pressurised using compressors, which will increase the storage capacity of the hydrogen pipes.



The options for line packing depend on pipe size and pressure.

STORAGE OPTIONS PER 100 KM

Pressure \ Size	36''	48''
35/20 bar	3,8-5,8 GWh	5,8-10,6 GWh
78/30 bar	10,1-11,5 GWh	17,8-20,9 GWh

Source: Brinkmann (2023)

5.4 Area limitations and other considerations

The construction of a hydrogen infrastructure in Denmark must take area limitations and nature protection into consideration.

Legislation provides for a wide range of aspects whereas others must be allowed for since they will add to the construction period and the associated costs. The area limitations and other considerations allowed for by the proposed hydrogen infrastructure are summarised in Box 5.5.

The development of the plan for constructing a future hydrogen infrastructure has taken market, political and technology aspects and also local and regional area limitations into consideration.

The sum of all these aspects has determined the priorities and design principles used by the CIP Foundation, including how, when and to what extent the hydrogen infrastructure should be built. The overriding design principle has been cost minimisation, i.e., the solution that will be least costly to society.

5.5 Distribution of energy potential, electrolysis capacity and hydrogen production

The long-term expansion plan is based on Denmark's potential for renewable energy and the expected future domestic consumption of both electricity and hydrogen.

The energy not used for direct electrification can be used to produce hydrogen, and the assumption is that the hydrogen that Denmark will not be able to use domestically will be exported to other countries, see the Market Assessment of the CIP Foundation (2023). A summary of Denmark's renewable energy production potential and domestic need can be seen in Box 5.7.

***Box 5.5:** The expansion must allow for multiple area limitations*

AREA LIMITATIONS AND OTHER CONSIDERATIONS

- Nature preservation areas, such as Natura 2000 areas and section 3 areas
- Dense urban areas
- Cultural heritage, such as ancient monuments
- Existing and planned energy infrastructure
- Traffic infrastructure
- Oil and gas activities
- Commercially important zones, such as fishery zones
- Military zones

***Box 5.6:** A generally higher threat level for the energy infrastructure*

SECURITY CONCERNS

Recent years have seen a marked rise in the threat against infrastructures in the sea and on the seabed, and with the blast of the Nord Stream gas pipes in 2022, the vulnerability of an offshore infrastructure became obvious.

A hydrogen infrastructure is found not to add to the vulnerability of supplies since this infrastructure over time will replace a fossil infrastructure with comparable properties, locations and vulnerabilities.

However, the added security threat should be addressed by the future hydrogen infrastructure through reinforcement of the very infrastructure using rock protection, more intense monitoring or patrolling, as examples.

Most likely this will add to the costs. As an example, protecting offshore hydrogen pipes with rocks would almost double the price per square metre.

Sources: The Danish Security and Intelligence Service (PET, the Danish Broadcasting Corporation (DR) and COWI.

***Box 5.7:** Renewable sources, potential and consumption in the long-term*

Hydrogen	Offshore	Onshore + nearshore		Total
Geographic location	The North Sea	Onshore	Bornholm	
Renewable energy for hydrogen production	52,5 GW[1]	22 GW	6,9 GW	81,4 GW
Electrolysis capacity	35 GW	15 GW	4 GW	54 GW
Annual hydrogen production	140 TWh	60 TWh	16 TWh	216 TWh
Denmark's consumption 2050		19 TWh		19 TWh
For exports	140 TWh	41 TWh	16 TWh	197 TWh

1 According to estimates produced by the Danish Energy Agency, the North Sea potential may total up to 52 GW for the currently screened areas, but the potential is found to be larger when new areas are screened and the overplanting option is introduced (https://ens.dk/sites/ens.dk/files/Vindenergi/offshore_wind_potential_in_the_north_sea.pdf)

A staged rollout plan

Chapter 6

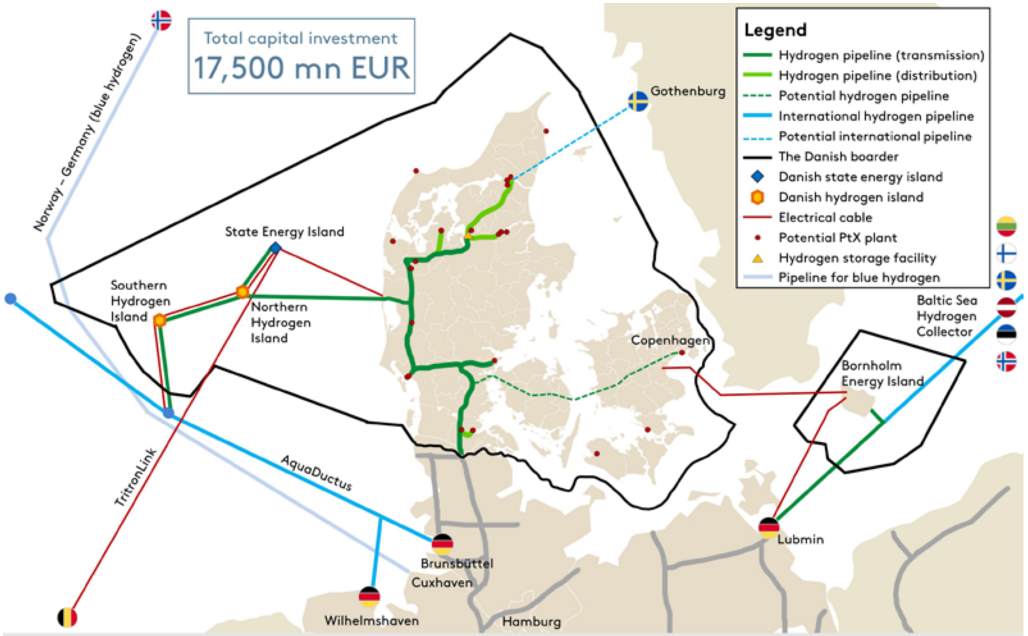
Based on the assumptions concerning technology and the market, design criteria, the international demand and Denmark's renewable energy potential, the CIP Foundation has developed a proposal outlining in concrete terms a coherent hydrogen infrastructure that encourages maximum utilisation of Denmark's renewable energy. This infrastructure will provide Denmark with an international interconnection and with this relevant export markets through connections to international projects. Figure 6.1 shows the comprehensive hydrogen infrastructure proposed by the CIP Foundation.

When fully built, this hydrogen infrastructure will release the full renewable energy potential and generate annual exports totalling about EUR 13.5 billion. This infrastructure is structured around three core branches which together will ensure stable production and supply.

THE NORTH SEA

In the North Sea, Denmark has the largest wind potential and the best opportunities to obtain cost-effective green hydrogen production. The cost benefits of hydrogen production are most significant for offshore energy islands, since (1) the electrical energy loss is reduced when the hydrogen production moves closer to the wind turbines; (2) the electrolysis capacity can be exploited better with a higher number of full load hours; and (3) the transmission costs are lower because it is less costly to transmit hydrogen than electricity.

Figure 6.1: *The proposed coherent hydrogen infrastructure, fully built*



The CIP Foundation's plan for a coherent hydrogen infrastructure
Fully completed by 2045

For these reasons, the CIP Foundation recommends building two dedicated hydrogen islands in the North Sea each with an electrolysis capacity of 15 GW and to install an electrolysis capacity of 5 GW on the energy island decided at the political level. The dimensions of the energy island pose a risk in that the island might be too small to ensure profitable hydrogen production. In this context it is worth noting that the intention is to build the state-owned energy island at the best site in the North Sea in terms of wind and seabed conditions.

Through their domestic and international interconnections, all of these islands will be able to transmit hydrogen to Germany and Denmark and electricity to Denmark, Germany and Belgium. The electricity cables in fact reflect a need to balance the energy system (the pipeline to Denmark) whereas the pipeline to Belgium is part of the political agreement concerning the state-owned energy island. Together, the three islands are expected to produce 65% of Denmark's hydrogen production in total, see Figure 6.2.

THE ONSHORE BACKBONE

Onshore and nearshore, Denmark has renewable energy potential far in excess of

the country's need for electricity. With this in mind, the CIP Foundation recommends that onshore hydrogen infrastructure should be built extending from the German-Danish border and northward through Jylland, Denmark, see Figure 6.1. The purpose of this infrastructure is to link a series of known and realistic hydrogen projects with Danish and German buyers and consumers. The expectation is that a total electrolysis capacity of 15 GW, equivalent to 28% of the Danish production, will be built in Jutland during the period leading up to 2045. After deduction of Denmark's hydrogen consumption, the hydrogen produced in Jutland will account for 20% of the total Danish hydrogen export potential. Since the hydrogen infrastructure in Jutland is linked to the North Sea, this infrastructure can take the pressure off the infrastructure around the islands during peak load periods, see Figure 6.3.

ENERGIØ BORNHOLM

Værdien af en dansk brintinfrastruktur ligger i udlandsforbindelserne, da det er adgangen til markedet. Derfor skal en dansk brintinfrastruktur omkring Bornholm samtænkes med Baltic Sea Hydrogen Collector, som forbinder Tyskland med Nordsverige og Finland.
I Østersøen er der et betydeligt vedvarende energi-potentiale bestående hovedsageligt af kystnær havvind. CIP Fonden anbefaler, at der etableres 4 GW elektrolyse på Bornholm med mulighed for transport af brinten gennem Østersøen og til Lubmin i Tyskland. Forventningen er, at produktionen på Bornholm vil udgøre 7% Danmarks samlede produktion, jf. figur 6.2.

> The recommendation is to integrate the hydrogen pipeline to Lubmin as the first step of the Baltic Sea hydrogen Collector.

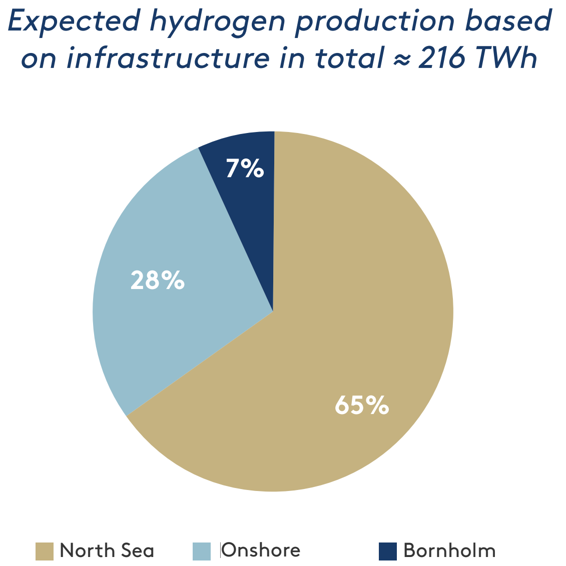
INTERNATIONAL INTERCONNECTIONS, DIMENSIONING AND TIMELY EXPANSION

Since more than 90% of Denmark's future hydrogen production will be exported, international interconnections are a core factor for a Danish hydrogen infrastructure. In parallel with this, supply and demand will grow over time and so the infrastructure has to be built in stages as it is the most cost-effective and market-creating method from a short- and also long-term perspective. Figure 6.4 shows the stages recommended by the CIP Foundation of an expansion process which will support the development of the market and exports and provide Denmark with an opportunity to benefit from a first mover advantage. The recommendation is a three-stage expansion process with a detailed review of the interconnections and dimensions of the infrastructure relative to the future hydrogen transmission, with the most important elements illustrated in Figure 6.4.

LONG-TERM EXPANSION PROCESS

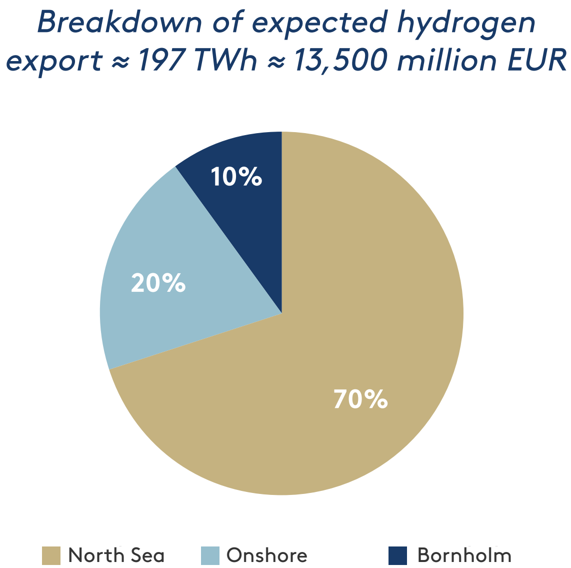
The expansion plan comprises three stages. The first one begins in 2024 and the last one will be finalised in 2045. The phases reflect both the market development and the political targets. By 2050, most countries must have fulfilled their climate targets and also several declarations have set targets for 2050, for example the Esbjerg Declaration and the Ostend Declaration. During the period until then, the demand for hydrogen and other green fuels will grow since the energy-intensive sectors have to transition. At the same time, the technological advances – for example in relation to electrolysis – will accelerate. This opens up some opportunities: Both during the initial stages when the market is not yet mature and towards the end of the period when green hydrogen will be a dominant energy carrier.

Figure 6.2: Hydrogen production by production sites



Source: COWI (2023)

Figure 6.3: Hydrogen exports by production sites



Source: COWI (2023)

INFRASTRUCTURE DIMENSIONS TO MEET LONG-TERM NEEDS

Although green hydrogen will become a fundamental energy carrier in society in the long term, the hydrogen and Power-to-X (PtX) industries are still in their infancy. The technology is immature and demand and supply are modest. Basically, the phase is intended to give viable hydrogen projects access to a hydrogen infrastructure which links them to the relevant buyers and consumers. This is the way to create a market with the potential to grow. In a medium-term perspective, the market will most likely be different. The industry and the market will develop, and production and demand will be scaled up if the market is given the required.

This means that the need for an infrastructure will change once green hydrogen becomes the dominant energy carrier in society. Already when building the initial infrastructure this must be taken into consideration. Consequently, the recommendation is to build an infrastructure of over-dimensions from the start to ensure that it can handle the expected long-term quantities. This will be cost-effective since building a single large hydrogen pipeline is less costly than building two smaller ones.

OPENNESS AS STRATEGY

Creating a long-term expansion plan, which is announced publicly, will provide producers, developers and investors with transparency and enable them to make plans for a defined, future infrastructure. Investment decisions are more easily made if you know the pipeline layout, its capacity and the conditions for connection and transmission. In parallel with this, Danish energy consumers can make their own decisions concerning the shift from fossil fuels to green hydrogen, which can generate a short-term increase in domestic demand. However, there could also be strategic advantages at international level:

Other countries have to start looking to Denmark as a supplier of green hydrogen, and infrastructure developers in other countries

Figure 6.4: *Order of expansion of the infrastructure*

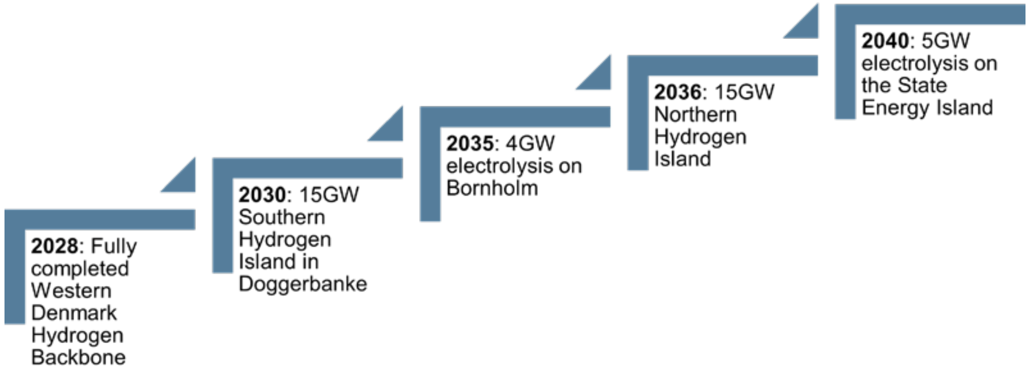
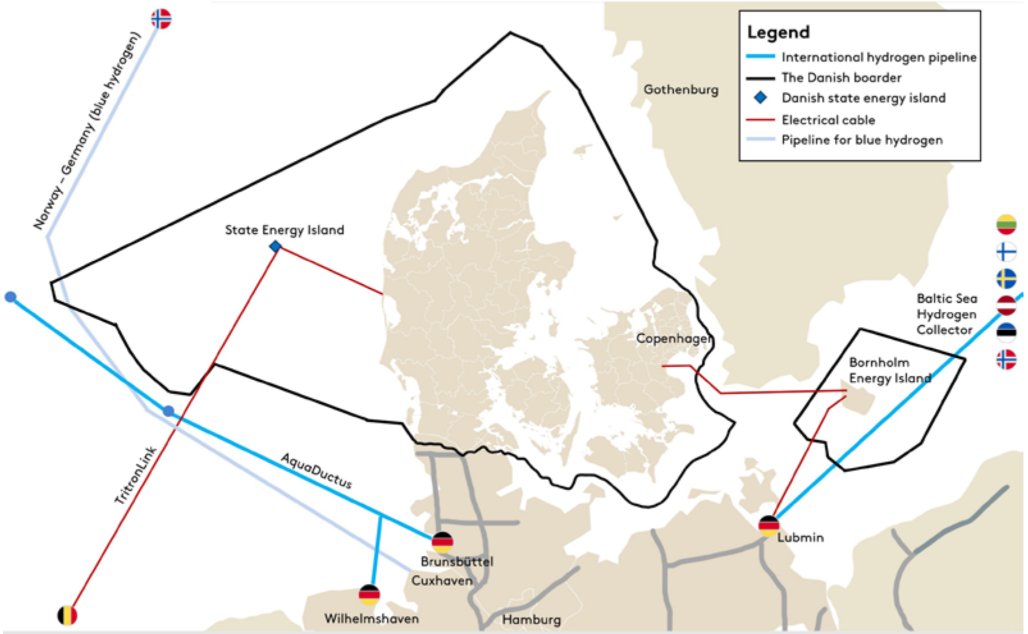


Figure 6.5: *Already planned infrastructure*



Already planned infrastructure

Box 6.1: *International hydrogen infrastructure plans included in the CIP Foundation's proposal*

2027 BORNHOLM-LUBMIN

German gas transmission operator Gascade is planning a hydrogen pipeline from Bornholm to Lubmin in Germany together with Copenhagen Infrastructure Partners and with the involvement of Energinet. The project started based on a feasibility study and the developers have submitted a PCI application to the European Commission. The Bornholm-Lubmin pipeline will cover a distance of 140 km. The interconnection is to transmit green hydrogen produced on Bornholm using electricity generated by the nearby offshore wind facilities to the shore close to Lubmin and from there further southwards. According to the plan, the pipeline will be operational by 2027, with an option to increase its capacity to 10 GW during the 2030s. Geographically, the Bornholm-Lubmin pipeline is a continuation of the 'Flow – making hydrogen happen' project which is a 1,100 km long pipeline in Germany. According to the plan, the first phase of 'Flow' will be ready by 2025.

2028 DENMARK-GERMANY

In April 2023, the Danish Minister for Climate, Energy and Utilities, Lars Aagaard, and Germany's Minister for Finance and Climate, Vice Chancellor Robert Habeck, signed a Letter of Intent (LoI) concerning transmission of hydrogen between Germany and Denmark. This LoI states that a large-scale, onshore transmission pipeline is to be installed between Western Denmark and Northern Germany before 2028. The exact location of the infrastructure and its scope remain to be determined, but the ambition is to strengthen the integration of the Danish and the German energy systems in order to generate a market-driven rollout of green hydrogen infrastructure.

2030 THE ENERGY ISLAND IN THE NORTH SEA

In 2020, a large majority in the Danish Parliament decided to build an energy island in the North Sea. The energy island is expected to be ready by 2030, and by 2033 the connected renewable energy capacity is expected to be 3-4 GW. According to the plan, the energy island will have direct electrical interconnections to Denmark and Belgium.

2030 BORNHOLM ENERGY ISLAND

In parallel with the decision to build an energy island in the North Sea, the Parliament also decided that Bornholm should become an energy island. Bornholm Energy Island is expected to be operational by 2030 featuring a capacity of 3 GW nearshore offshore wind located about 15 km south-southeast of the island. The electricity will be transformed on Bornholm and then transmitted via electrical cable to the Danish island of Zealand and to Germany.

2030 THE BALTIC SEA HYDROGEN COLLECTOR

According to plans made by Gasgrid Finland, Nordion Energi, OX2 and Copenhagen Infrastructure Partners, the Baltic Sea Hydrogen Collector project (BHC) will be operational by 2030. BHC is an offshore hydrogen interconnection which on its route through the Baltic Sea will interconnect regions in Finland and Sweden with Germany. According to the plan, the hydrogen pipeline will run in parallel with the pipeline between Bornholm and Lubmin and is also expected to end in Lubmin.

2030 AQUADUCTUS

In the North Sea, German Gascade and Belgian Fluxys are planning a 400 km hydrogen pipeline which will reach the shore at two spots in Northern Germany. From these connection points, North Sea hydrogen is expected to be transmitted further into Germany or to other countries, such as the Netherlands or Belgium. This pipeline will extend to relevant offshore wind sites in the North Sea via Helgoland and to Dogger Bank where it will be possible to connect the pipeline to pipelines from other countries, such as the UK and Denmark. The plan says that the interconnection will start delivery of green hydrogen to the mainland in 2030.

2030 NORWAY-GERMANY

At the beginning of 2023, German RWE and Norwegian Equinor entered an agreement to install a submarine hydrogen pipeline through Danish territorial waters. To begin with the pipeline will be supplying Germany with blue hydrogen directly from Norway in 2030. From a long-term perspective, the pipeline is expected to deliver green hydrogen to Germany.

Sources: The Danish Ministry for Climate, Energy and Utilities (2023a, 2023b), RWE (2023), Energinet (2023) and the Market Assessment of the CIP Foundation can include Denmark's hydrogen infrastructure in their planning. Announcing long-term plans to the public provides Danish players with an advantage, and likewise a Danish hydrogen infrastructure can come to play a role as a strategic hub in the international planning process.

INTERNATIONAL INTERCONNECTIONS ARE CRUCIAL TO THE REALISATION OF MARKET POTENTIAL

The plans for establishing hydrogen pipelines are advanced in the countries around Denmark. Since international interconnections are crucial to ensure that Denmark can realise its market potential, the international plans have been included as critical to the expansion plan recommended by the CIP Foundation. A connection to international projects can be a cost-effective solution and a gateway to the market. The international plans for a hydrogen infrastructure, which will be included in the development plan, are described in Box 6.1 overleaf.

> The recommendation is to establish a fully expanded Western Danish infrastructure ready for operation by 2028, capable of delivering to buyers and consumers in Denmark and Germany from the onset.

6.1. Phase 1 – 2024-2028: Onshore hydrogen infrastructure with a Danish backbone

MUCH EXPECTED FROM DANISH HYDROGEN PRODUCTION

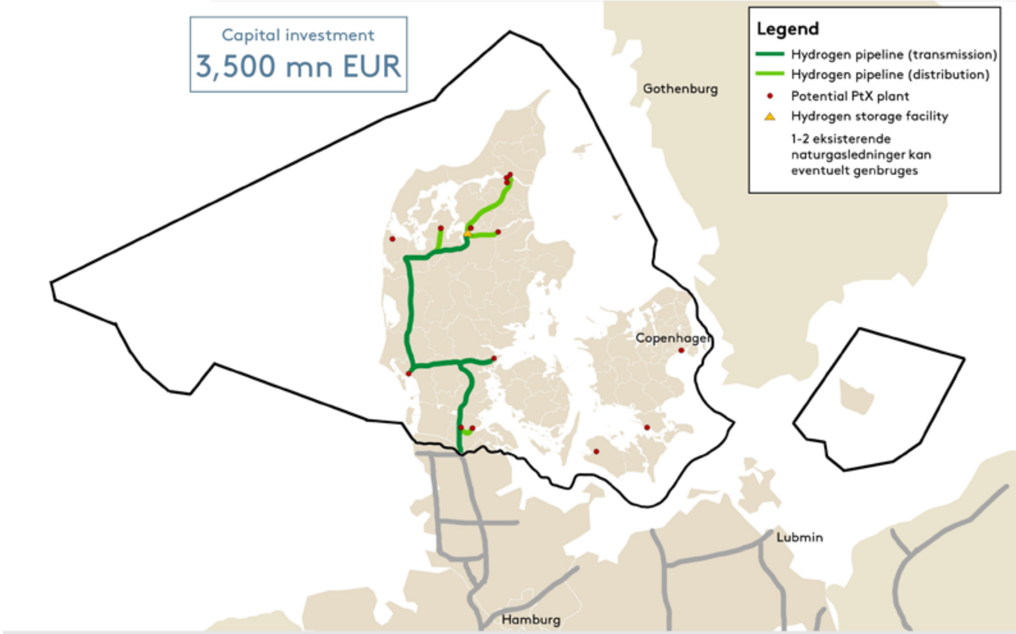
Between 2027 and 2028, the Danish onshore hydrogen production is expected to increase sharply, up towards 28 TWh a year, if the producers are given access to an infrastructure[1]. Today, the plans only comprise a limited cross-border hydrogen infrastructure from Western Denmark to Northern Germany, which will not suffice to link the Danish producers with the German consumers. If Denmark is to make the most of its potential during this period and make its contribution to the development of the industry, the onshore infrastructure has to be built out a lot more.

FROM GERMANY TO NORTHERN JUTLAND – A WESTERN DANISH BACKBONE BY 2028

In the short term, up to 2028, a Danish hydrogen infrastructure should be land-based since this is where it will be possible to produce sufficient quantities of green hydrogen during the period. This infrastructure must be able to fulfil several purposes. It must be able to collect hydrogen from various hydrogen producers in Denmark and provide a connection to the consumers. The Danish consumers will for the most part be producers of e-fuels and ammonia and in the long term also major industrial producers which today consume large quantities of coal or gas and could transition using green hydrogen from a Danish hydrogen infrastructure. The largest consumers, however, are found south of the Danish-German border and for this reason an international interconnection to Germany is a core element. More than half of the hydrogen to be produced during this period will be exported to countries south of the Danish border.

In view of this, the CIP Foundation proposes that a Danish hydrogen infrastructure connects Germany with Northern Jutland already by 2028. The proposed route extends from Northern Jutland to Vejen in Denmark. From Vejen the pipeline stretches across Jutland linking Fredericia in the east with Esbjerg in the west. From this point the pipelines goes

***Figure 6.6:** Illustration of phase 1 of the expansion of the Danish hydrogen infrastructure, 2024-2029*



Phase 1: 2024-2028
The Western Denmark hydrogen backbone

to Holstebro where it exits into the sea with the option to connect the pipeline to the salt cavern at Lille Torup which can act as a large-scale green hydrogen storage facility. From the section into the country from Holstebro and the storage facility at Lille Torup, it is proposed to build minor branches to Northern Jutland in order to connect the hydrogen producers in Northern Jutland with the German market.

DIMENSIONING AND LINEPACK

The proposed infrastructure consists of newly installed hydrogen pipes with the main pipeline comprising 48" 18 GW transmission pipes. Via smaller distribution branches, the infrastructure connects a large share of the future onshore hydrogen producers to the German market and similarly Danish hydrogen consumers can be connected to smaller branches as required. This transmission pipeline can carry 157 TWh a year and store an additional 57.1 GWh hydrogen by applying a pressure of 80 bar[2]. The storage facility at Lille Torup can provide additional linepack capacity of 350 GWh. In this way, the infrastructure is capable of handling the 28 TWh a year which Danish producers are expected to be able to produce. Of these 28 TWh, Denmark is expected to export 16 TWh in 2030. During peak load periods, the transmission pipes can manage 15 GW, although peak loads are expected to not exceed 7 GW in 2030[3].

Also in 2050, when hydrogen production from 15 GW electrolysis capacity will be able to produce 60 TWh, the pipe will have the dimensions required to manage the expect-

1 KPMG for Energinet and Evida (2022)
2 Based on COWI (2023b)
3 Based on the CIP Foundation (2023): In 2030, an onshore capacity of 7 GW is expected to generate a production of 28 TWh.

Dimensions and storage capacity

Transmission pipe: 48"/18 GW ≈ 157 TWh a year.

Pipeline storage (linepack): 57.1 GWh at 80 bar

Storage in Lille Torup cavern: 350 GWh

Distribution pipes: 4"–8", 10"–18" & 20"–30"

ed quantities. Consequently, the pipe is of over-dimensions for the entire period until 2050 with the intention that the pipe can also be used for the transmission of hydrogen produced in the North Sea. During the initial stages when the pipe is over-dimensioned compared with the expected production, the infrastructure as such can provide storage capacity and so the storage at Lille Torup is not necessary for the market players.

The onshore hydrogen infrastructure is expected to pave the way for the development of the Danish hydrogen industry which will then generate energy exports amounting to about EUR 1 billion a year in 2030, and potential exports of EUR 2.4 billion a year in 2050 based on annual exports of 41 TWh[4].

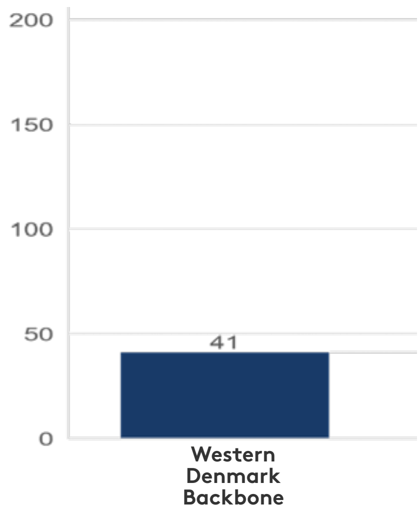
ALTERNATIVE OPTIONS FOR THE PERIOD 2024-2028

A dual gas pipeline exists close to the route in Southern Jutland. One of these pipes could be taken out of service and retrofitted to be used for a hydrogen infrastructure. This would reduce the construction costs of this phase[5]. This solution is rejected because the capacity that a retrofitted gas pipe could provide is insufficient to meet the future export capacity required for the supplies from Jutland and also the North Sea.

Furthermore, newly installed pipes will help increase the linepack to the benefit of the producers in Southern Jutland. To this should be added that the number of buildings and environmental zones surrounding the present gas corridors have multiplied which makes retrofitting more difficult.

For the phase in central Jutland, the pipeline can also be installed alongside the present gas corridors in this part of Denmark. A route of this type would extend from the section to Lille Torup without reaching the western coast. Since reuse of gas pipes is not an option for this section, new dedicated hydrogen pipes would still have to be installed. The investment need will be different, however; the transmission pipeline will be shorter whereas a higher number of branches will be required if the same quantity of hydrogen has to be collected along the western coast of Jutland. This form of route was not selected in order to ensure a location close to the infrastructure of future producers, the renewable energy potential as well as the transformer stations and electricity coupling points located along the western coast of Jutland. Furthermore, installing hydrogen pipes in the existing gas corridors would be problematic considering the number of buildings and environmental zones[6].

***Figure 6.7:** Expected hydrogen exports based on the hydrogen infrastructure in 2028 (TWh)*



Phase 2 – 2029-2035: Expanding offshore and building international interconnections

SEVERAL INFRASTRUCTURE PROJECTS ON THE WAY BUT PLANNED PRODUCTION IS LIMITED

Several major hydrogen infrastructure projects are scheduled for completion during the years following 2030. These hydrogen infrastructure projects are a result of the strong demand from Germany, the Netherlands and Belgium.

The demand for hydrogen presented by Germany, the Netherlands and Belgium is expected to double by 2030 compared with 2020. In parallel with this, by 2030 Denmark will have covered its domestic hydrogen consumption with the hydrogen produced and distributed through the onshore backbone. However, Germany, the Netherlands and Belgium are not in a position to produce all of the green hydrogen required to cover their consumption. They will need to import hydrogen from for example Denmark which thanks to its good wind conditions and shallow waters is able to produce the cheapest hydrogen of all the North Sea countries.

It is recommended to build a hydrogen island at Dogger Bank in the North Sea around 2030.

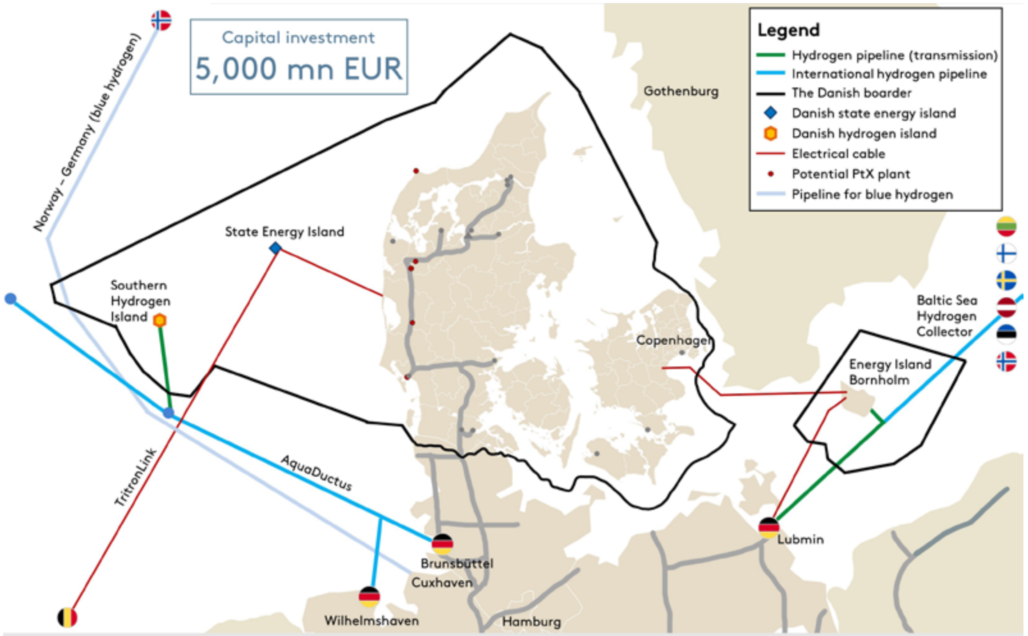
4 Own calculations based on the CIP Foundation (2023) and COWI (2023a and 2023b). By 2050, Denmark's domestic consumption of hydrogen is expected to total about 19 TWh and the production in Western Denmark is expected to reach 60 TW.
5 Brinckmann (2023)
6 COWI 2023b

DANISH LARGE-SCALE PRODUCTION – A HYDROGEN ISLAND AT DOGGER BANK
In the light of the above, the CIP Foundation recommends that Denmark should begin to exploit the North Sea resources for large-scale production of green hydrogen already during this period and that a dedicated hydrogen island should be located at Dogger Bank, the Southern Hydrogen Island. The construction of the island should be timed for operation of up to a 15 GW electrolysis capacity in 2030, three years before the state-owned energy island will be ready to come on stream with a capacity of 3-4 GW. Since the primary objective of the hydrogen island at Dogger Bank should be exports, the island can be built, owned and operated on commercial terms. For precisely this reason, the location of the island at Dogger Bank is a key point; the wind conditions are good, the waters are shallow and add to this the short distance to Northern Germany where there will be a demand for the hydrogen.

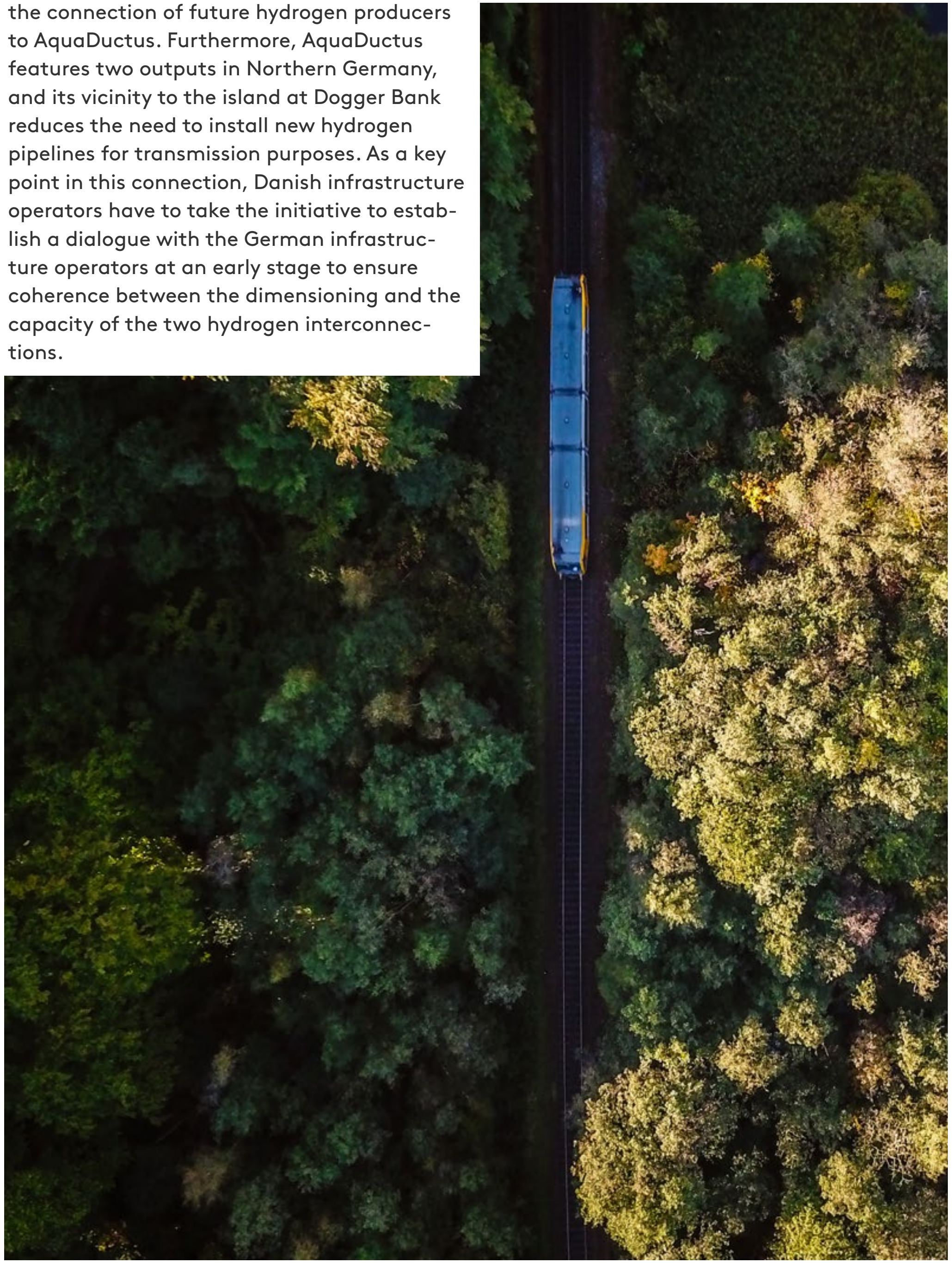
KEY INTERNATIONAL INTERCONNECTIONS
The hydrogen island at Dogger Bank has to be connected to the German mainland where the energy-intensive German industry can consume all of the capacity, or the hydrogen can be transmitted to the markets in the Netherlands or Belgium. The CIP Foundation recommends that the hydrogen island should be connected to AquaDuctus which is expected to supply the market with green hydrogen from 2030.

The hydrogen pipeline should be over-dimensioned from the onset, 48” 18 GW, to ensure the connection of future hydrogen producers to AquaDuctus. Furthermore, AquaDuctus features two outputs in Northern Germany, and its vicinity to the island at Dogger Bank reduces the need to install new hydrogen pipelines for transmission purposes. As a key point in this connection, Danish infrastructure operators have to take the initiative to establish a dialogue with the German infrastructure operators at an early stage to ensure coherence between the dimensioning and the capacity of the two hydrogen interconnections.

Figure 6.8: *Illustration of phase 2 of the expansion of the Danish hydrogen infrastructure, 2029-2035*



Phase 2: 2029-2035
Expansion of the Danish hydrogen infrastructure offshore and abroad



ALTERNATIVE WAYS OF CONNECTING A HYDROGEN ISLAND TO GERMANY

If the AquaDuctus project is not realised, the hydrogen island could instead be connected to the Norwegian-German interconnection or directly to the German mainland. If the hydrogen island is connected to the German mainland, the investment required to build the pipeline will be significantly higher – EUR 1.5 billion. On a positive note, however, the island could become a strategic point of common coupling for other renewable energy productions in the North Sea, if given the right dimensions. Another option is to connect the Southern Hydrogen Island to the Norwegiany-German hydrogen interconnection transmitting grey hydrogen. This would require that the pipeline bypasses a listed section of the German part of Dogger Bank. The CIP Foundation does not recommend this approach because of the nature of the Norwegian-German interconnection which is the result of a collaboration agreement between the two countries, whereas the ambition with AquaDuctus is to collect hydrogen from whoever is able to deliver in that area. Consequently, the conclusion is that Danish players have better potential for increasing the dimensions of AquaDuctus if Denmark is able to present a specific production plan.

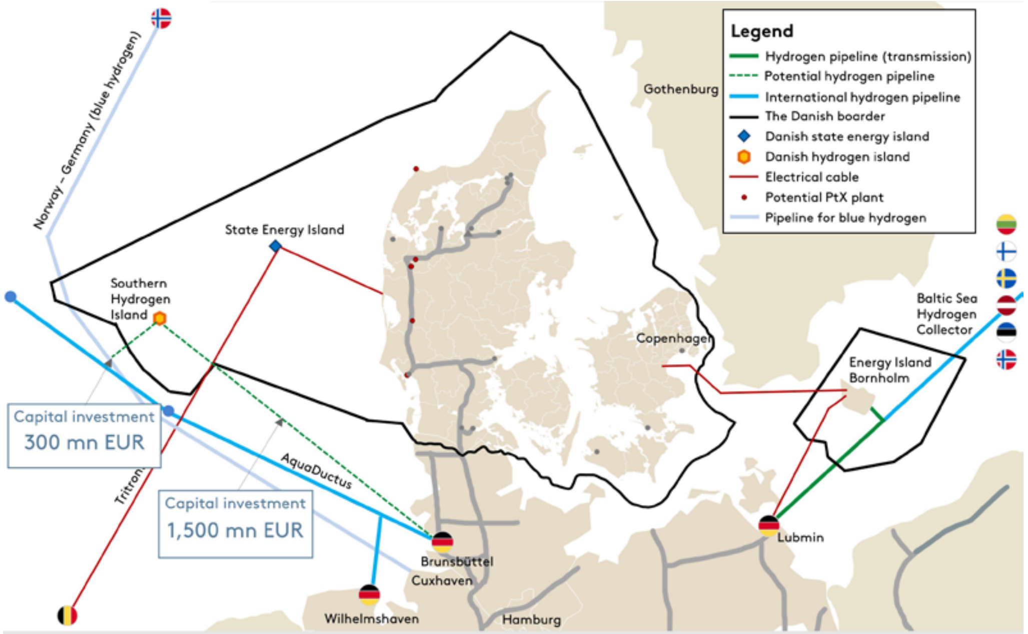
EXPORTS AND THE TRANSITION OF GERMAN INDUSTRY

With the Southern Hydrogen Island and a hydrogen pipeline to Germany, Denmark would be able to export considerable quantities of green hydrogen for the transition of the manufacturing industries in Germany, the Netherlands and Belgium. If the 15 GW of electrolysis capacity on the Southern Energy Island is realised, Denmark would be able to export another 60 GW a year.

The nearshore wind energy production in the Baltic Sea also provides the basis for production of hydrogen on Bornholm. The hydrogen can be transmitted via the pipeline between Bornholm and Lubmin which should be dimensioned for 36", equivalent to 10 GW. These dimensions are excessive in view of the production expected on Bornholm but will make it possible to add hydrogen transmitted via the Baltic Sea Hydrogen Collector in the Baltic Sea.

It is recommended that hydrogen production should be established on Bornholm equivalent to 4 GW electrolysis by 2035.

***Figure 6.9:** Illustration of alternative interconnections from the Southern Hydrogen Island to Germany during phase 2 of the expansion process*



Phase 2 (two alternative connections): 2029-2035
The hydrogen Island connects to AquaDuctus at shortest point or directly to Germany

DIMENSIONS

Southern Hydrogen Island: 15 GW electrolysis, 22.5 GW wind. Renewable energy can be transmitted from Danish or international sites around Dogger Bank.

Transmission pipe: Southern Hydrogen Island – AquaDuctus, 84 km: 48"/18 GW ≈ 157 TWh a year.

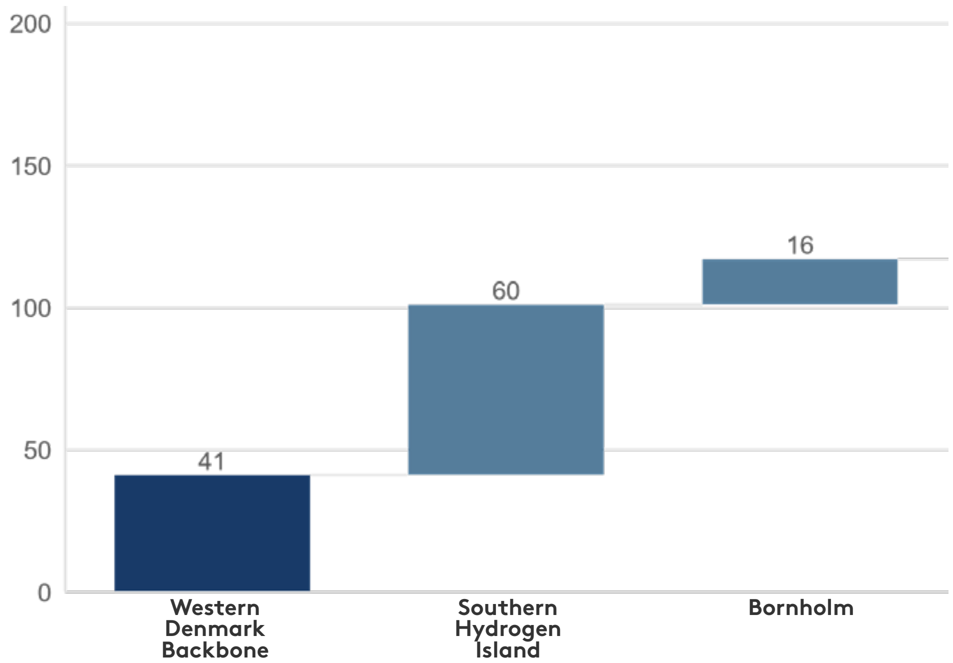
DIMENSIONS

Bornholm: 4 GW electrolysis, 6 GW wind

Transmission pipe: Bornholm-Lubmin, 162 km: 36"/10 GW ≈ 87 TWh a year.

Source: COWI (2023b)

Figure 6.10: *Expected hydrogen exports based on the hydrogen infrastructure in 2035 (TWh)*



Source: COWI (2023)

6.3 Phase 3 – 2036-2045: Scale, more pipelines and balancing

The key point in the third and final phase of the CIP Foundation's expansion plan is the construction of a Northern Hydrogen Island in the North Sea in order to upscale the hydrogen production even more and also the installation of multiple pipelines to benefit from synergies and ensure better balancing of the production of hydrogen and of electricity.

Phase 3 does not involve plans to establish additional infrastructure. On the other hand, much of the infrastructure already detailed could be given dimensions suitable to manage larger quantities of hydrogen.

This also applies to the interconnection between Norway and Germany which is expected to be given dimensions suitable for 10 GW[7] by 2038 whereas the state-owned energy island is expected to reach a capacity of 10 GW by 2040.

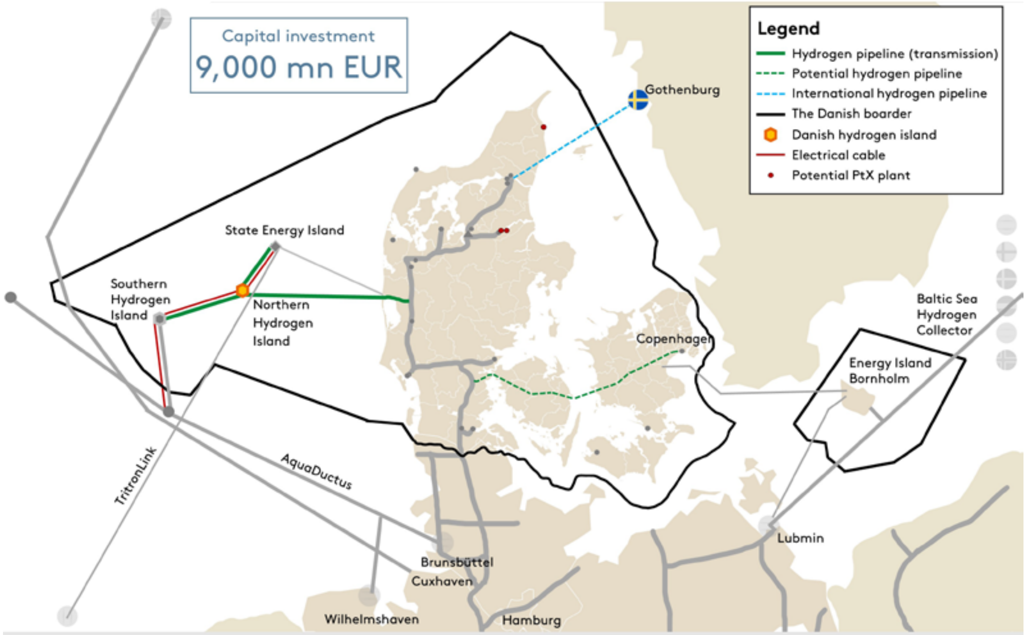
Generally, this period is expected to see substantial expansion of the North Sea wind capacity since the national climate targets and the targets set out in international declarations are moving closer. An example is the Ostend Declaration which targets an installed wind capacity of 300 GW in the North Sea alone before 2050 with all countries reaching climate neutrality. The massive expansion sets considerable demands for the hydrogen production and the balancing.

THE NORTHERN HYDROGEN ISLAND

The CIP Foundation proposes that one more hydrogen island, the Northern Hydrogen Island, should be built in the North Sea between the state-owned energy island and the hydrogen island at Dogger Bank. Like the Southern Hydrogen Island, the Northern Energy Island should be dedicated to the production of hydrogen with a 15 GW electrolysis capacity to produce green hydrogen for exports. The reason for this is that even with a massive expansion of the Northern European electricity grid, the capacity will not be sufficient to be able to transmit the energy resulting from the planned wind production expansion. At the same time, the countries will need more green hydrogen for the transition of energy-intensive industries and the transport sector. And with wind energy

> It is recommended that hydrogen production is expanded by establishing a Nothern Hydrogen Island in the North Sea by 2036

***Figure 6.11:** Illustration of phase 3 of the expansion of the Danish hydrogen infrastructure, 2036-2045*



Phase 3: 2036-2045
Scalling up production, multiple connections and balancing network

7 RWE (2023)

expanding so massively in the North Sea, exploitation of the synergies between the production of hydrogen and electricity becomes even more imperative.

THE NORTHERN HYDROGEN ISLAND AS BALANCING CENTRE

The CIP Foundation recommends that the Northern Hydrogen Island should be connected to the Southern Hydrogen Island at Dogger Bank via a hydrogen pipeline with the result that hydrogen produced on this island can be exported along this pipeline to AquaDuctus and then to Germany, the Netherlands and Belgium.

At the same time, the Northern Hydrogen Island should be connected to both the Southern Hydrogen Island and the state-owned energy island using electric cables. This will make it possible to exchange electricity between the three islands whenever this is an advantage. In this way, all three islands can transmit electricity to Denmark and Belgium,

DIMENSIONS

Northern Hydrogen Island: 15 GW electrolysis, 22.5 GW wind

Hydrogen transmission pipeline: The Northern Hydrogen Island – the Southern Hydrogen Island, 78 km: 36"/10 GW ≈ 157 TWh a year.

Hydrogen transmission pipeline: The Northern Hydrogen Island – the onshore backbone, 128 km: 36"/10 GW ≈ 87 TWh a year

The Northern Hydrogen Island – the Energy Island, 53 km: 36"/10 GW ≈ 87 TWh a year

Source: COWI (2023b)

when the need arises, and the state-owned energy island can use the excess electricity to produce hydrogen on the two hydrogen islands.

The establishment of the Northern Hydrogen Island with an electrolysis capacity of 15 GW will allow exports of an additional 60 TWh hydrogen a year.

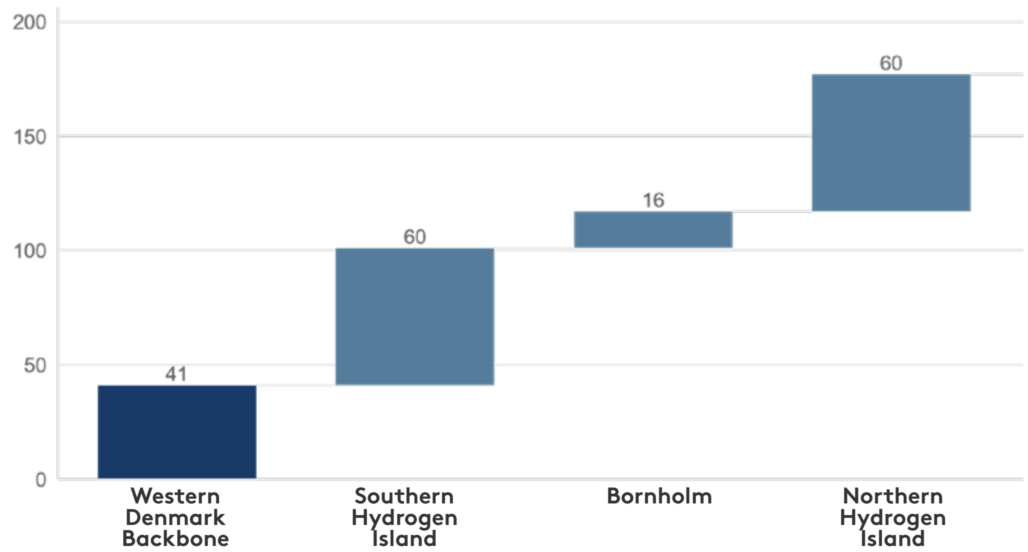
AN INTEGRATED SYSTEM

In terms of timing, the Northern Hydrogen Island should preferably be put on stream in 2036 so that this island is ready to take over the existing electricity from the state-owned energy island. The capacity of the state-owned energy island is expected to increase by 6-7 GW between 2033 and 2040; whether all of this energy can be sold as electricity depends on the number of international interconnections to be built. With an electricity interconnection from the Northern Hydrogen Island, excess electricity from the state-owned energy island can be exploited from the very beginning and in small quantities initially, which would not otherwise give rise to dedicated electrolysis on this island. This could improve the business case for the state-owned energy island where the excess energy would otherwise be lost for a period of time.

By 2040, when the state-owned energy island reaches its full capacity of 10 GW, Denmark's onshore and nearshore energy is expected to have been expanded to a degree where it will cover Denmark's domestic energy consumption. The CIP Foundation recommends that 5 GW electrolysis should be established on the energy island and that more of the electricity produced closer to the shore is included in the conventional electricity supply.

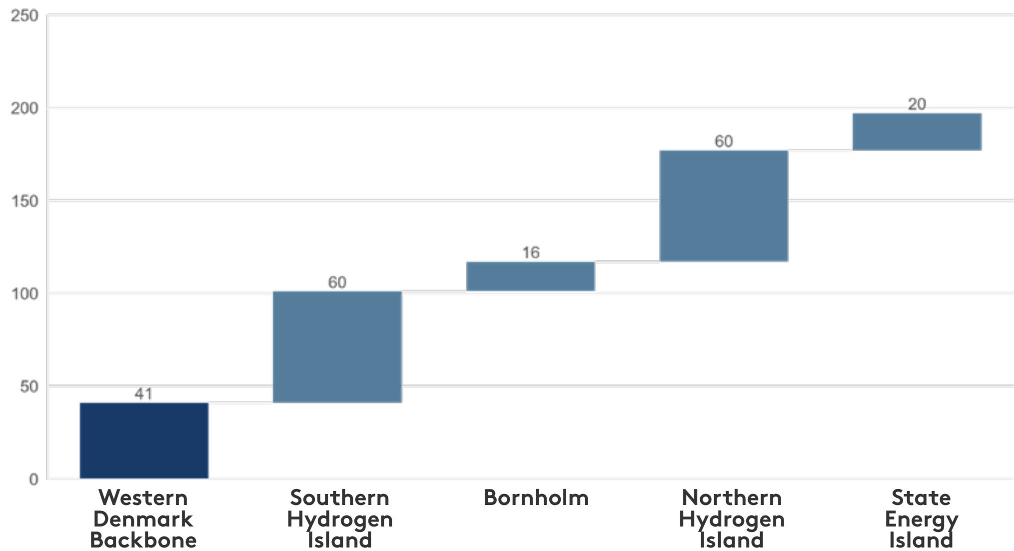
The energy island should be provided with a hydrogen pipeline to the Northern Hydrogen Island in order to be able to sell the hydrogen

***Figure 6.12:** Expected hydrogen exports based on the hydrogen infrastructure in 2036, TWh*



Source: COWI (2023)

***Figure 6.13:** Expected hydrogen exports based on the hydrogen infrastructure in 2040, TWh*



Source: COWI (2023)

to Germany via AquaDuctus. The dimensions of the pipeline from the Southern Hydrogen Island to AquaDuctus allows the transmission of the annual production of 140 TWh. Since peak load periods may pose a challenge, it is recommended to install a hydrogen pipeline from the Northern Hydrogen Island to the onshore backbone. This would enable the use of the available onshore capacity and ensure a sturdier infrastructure protected against pipe breakdowns and security threats.

With a 5 GW electrolysis capacity on the planned state-owned energy island in the North Sea, exports could amount to 20 TWh a year. The expansion plan as a whole facilitates production for exports of almost 200 TWh a year at a value of EUR 13.5 billion a year.Since the international community and with this also the international interconnections will be key to the expansion plan, Denmark has to make an effort to ensure their realisation.

AquaDuctus and the Bornholm-Lubmin pipeline are both international interconnections which according to the CIP Foundation's recommendations should be connected to a Danish hydrogen infrastructure. Although there are several options and alternatives to these interconnections, these two are found to be the most attractive ones as regards location and planning. Consequently, it is absolutely imperative to strive to ensure realisation of the plans and to ensure that the pipelines are given the dimensions that will allow them to manage the quantities to be exported from Denmark.

The exact dimensions of these two interconnections will depend not only on the Danish production but also on the production from other countries.

As a minimum, the dimensions of AquaDuctus should be 48" 18 GW and those of the Bornholm-Lubmin pipeline 36" 10 GW.

THE ISLAND OF ZEALAND AND SWEDEN

Multiple variables present themselves when it comes to the transmission of the future hydrogen quantities across Denmark and Sweden. The need to transmit hydrogen across Denmark is likely to arise, for example in the event of considerable production of green Power-to-X (PtX) fuels on the island of Zealand in Eastern Denmark where PtX production will not as such have access to the requisite quantities of renewable energy which can be produced in Jutland and in the North Sea.

In parallel with this, a regional need to import green hydrogen may arise in Sweden. Although Sweden does not basically expect the country to become an importer of green hydrogen, the need might arise because Swedish regional energy infrastructures are only interconnected to a limited degree. As an example, this could generate a need for limited imports from Denmark to Gothenborg and furthermore a hydrogen pipeline in Denmark could be an attractive source for balancing purposes in Sweden.

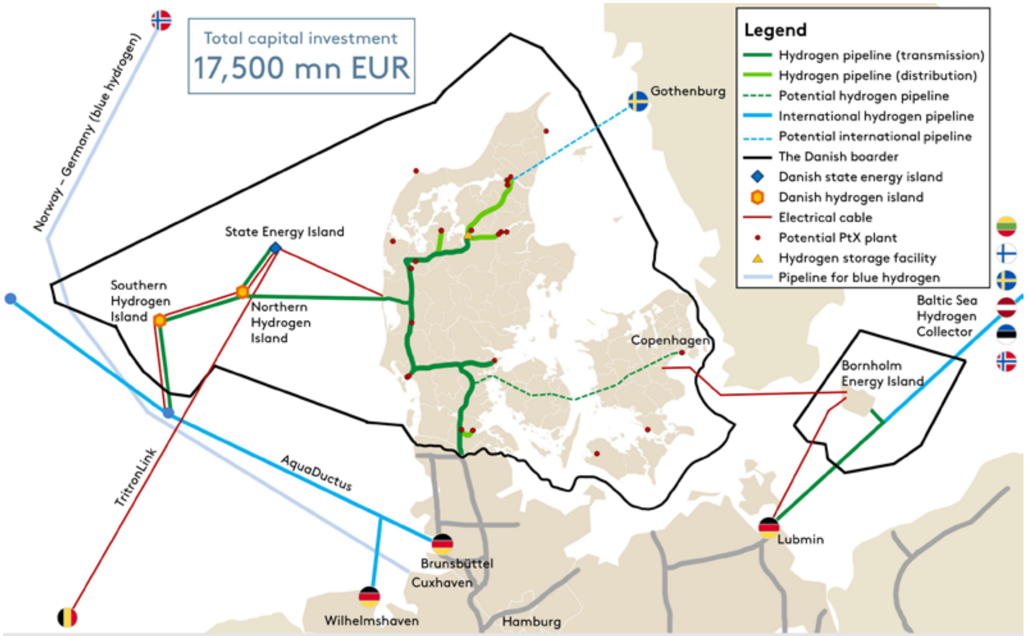
Since an interconnection from Northern Jutland to Gothenborg would be of interest to Sweden primarily, the planning and funding of such an interconnection should be made at the initiative of Sweden.

AN INTEGRATED NETWORK

The CIP Foundation's roll-out plan will provide Denmark with a fully integrated hydrogen network which will allow large-scale hydrogen production and exports to attractive markets ready to buy the hydrogen. Building the onshore backbone first will help support the development of the hydrogen producing industry i Denmark. Via this interconnection, the hydrogen producers will have access to the market in Germany, and future Danish industrial consumers can connect to the network.

It is recommended to establish hydrogen production on the planned state-owned energy island in the North Sea in 2040.

Figure 6.14: *Illustration of the complete Danish hydrogen infrastructure after the expansion process, 2045*



The CIP Foundation's plan for a coherent hydrogen infrastructure
Fully completed by 2045

DIMENSIONING THE INFRASTRUCTURE

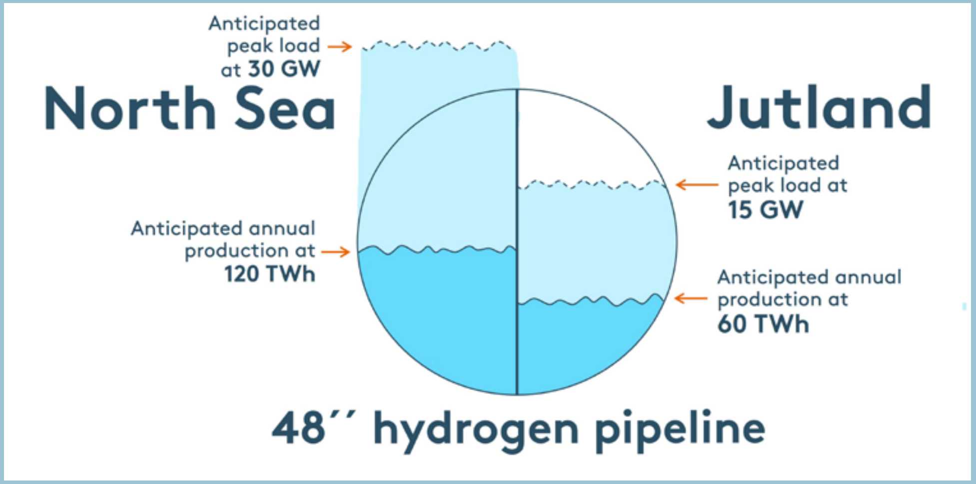
The dimensions of a coherent hydrogen infrastructure presented in the proposal are designed to manage the quantities of green hydrogen, which Denmark will be able to produce when exploiting the renewable energy potential, and to meet the political ambitions.

Initially, the infrastructure will be of over-dimensions but when fully established it will be able to both manage the expected annual production and the peak load production likely to be relevant at times when the electricity consumption is low and the production high.

The pipeline near Bornholm and in Jutland can manage both the annual average production and the likely peak load demand. Thanks to the dimensions of the international interconnection between the Southern Hydrogen Island and AquaDuctus, this interconnection will be able to manage the expected annual production, although on its own this pipeline will be unable to manage the most significant peak load periods.

During peak load periods, the quantities can be managed by (1) transmitting excess hydrogen to the Northern Hydrogen Island and through Jutland; (2) increasing the electricity production while reducing the hydrogen production; and (3) increasing the pressure in the pipes and in doing so increasing the capacity of the pipeline. All three possibilities are open due to the infrastructure's internal pipelines. Together they provide a valuable balancing capacity and individually these possibilities can be appropriate, depending on the current demand and production.

Figure 6.15: *The infrastructure can manage the expected annual production and peak load periods*

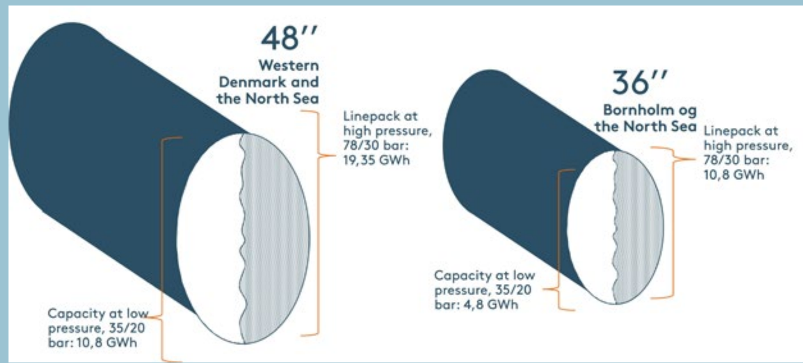


PIPELINE LINEPACK

According to the proposal, the infrastructure should be built mainly with 48″ pipes. This will provide twice the linepack compared with 36″ pipes. The linepack can be increased by increasing the pipe pressure. This provides various storage options.

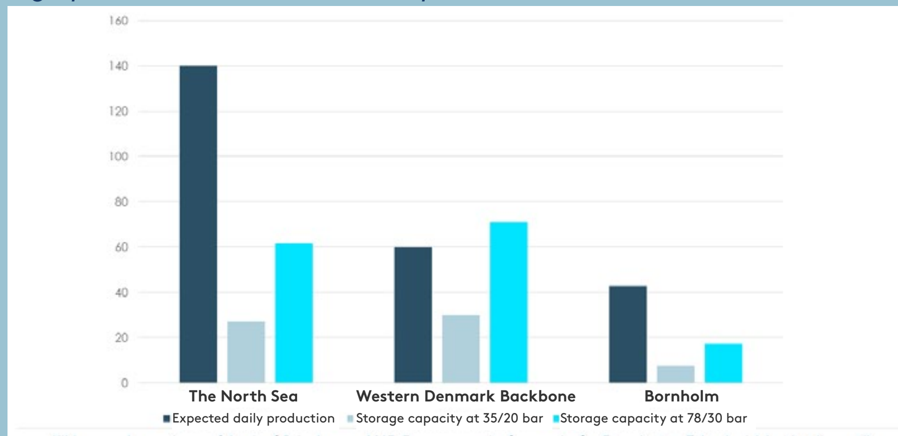
At a low pressure, the linepack of the pipeline forming the proposed onshore backbone is 30 TWh which increases to a linepack of 70 TWh at a high pressure. This is equivalent to a linepack for the expected production of half a day and of more than a full day, respectively. Using the interconnection between the Northern Hydrogen Island and the onshore backbone, this linepack can be exploited for hydrogen produced in both the North Sea and in Jutland. When fully expanded, the North Sea infrastructure will be able to store about 20% of the expected quantity of a full day's production at a low pressure which can be increased to more than 40% of a full day's production at a high pressure. Similar figures apply to the infrastructure interconnecting Bornholm and Lubmin.

***Figure 6.16:** The hydrogen pipelines can be pressurised to manage larger quantities of hydrogen when required*



Source: Own calculations based on Brinckmann, 2023. Based on an average of scenarios provided by the Danish TSO, Energinet, and the Danish Technological Institute.

***Figure 6.17:** The infrastructure can serve as storage at times with high production and low consumption*



Source: Own calculations based on Brinckmann, 2023. Based on an average of scenarios provided by the Danish TSO, Energinet, and the Danish Technological Institute.

PART 3

What does the hydrogen infrastructure cost? and what are the risks and possible rewards?

CIP fonden

Overall need for investment

Chapter 7

The development plan in three stages from 2024 to 2045 presented in Chapter 6 has been prepared based on the expected demand from south, Denmark's potential as well as Danish and international infrastructure plans already known at this point. The overall need for investment in a hydrogen infrastructure is spread across various infrastructure elements: (1) Some have already been enacted in Denmark, such as the Danish state energy islands in the North Sea and on Bornholm, (2) the potential international interconnections which Denmark may join and (3) recommendations from the CIP Foundation of a further expansion of the hydrogen infrastructure. The recommendations regarding hydrogen infrastructure involve significant investment costs. The greatest need for investment relates to the construction of hydrogen islands which are considered necessary to deliver on the political ambitions regarding renewable energy, big-scale production and the subsequent export of green hydrogen. In the following sections the need for investment will be accounted for based on the CIP Foundation's recommendations (3) regarding the establishment of a hydrogen infrastructure, including the need for investments in alternative solutions. This statement will include investments in hydrogen pipes, the construction of energy islands and hydrogen islands, the related electric cables and the derived need for electrical reinforcements caused by the infrastructure. Is should be noted that the hydrogen infrastructure only shows interconnections in the form of transmission pipes and does not include any private lines to producers or buyers of hydrogen. The statement does not include the need for investments in the expansion of the necessary renewable energy and related electrolysis as these investments are related to the production side. Moreover, the costs related to already enacted infrastructure plans (1) have not been included.

Price catalogue

The hydrogen infrastructure consists of some core elements which can be seen listed below as standard lengths and fixed prices. The catalogue is based on Brinckmann (2023) and the European Hydrogen Backbone (2022). The prices in the catalogue include establishment costs.

Element	CAPEX, mn EUR	
24", hydrogen pipeline, 100 km.	170	Onshore
36", hydrogen pipeline, 100 km.	250	Onshore
48", hydrogen pipeline, 100 km.	330	Onshore
Compressor, 10 GW	730	Onshore
24", hydrogen pipeline, 100 km.	250	Offshore
36", hydrogen pipeline, 100 km.	370	Offshore
48", hydrogen pipeline, 100 km.	450	Offshore

Source: COWI (2023b)

7.1. The need for investment during the first phase, 2024-2028 – the onshore hydrogen infrastructure

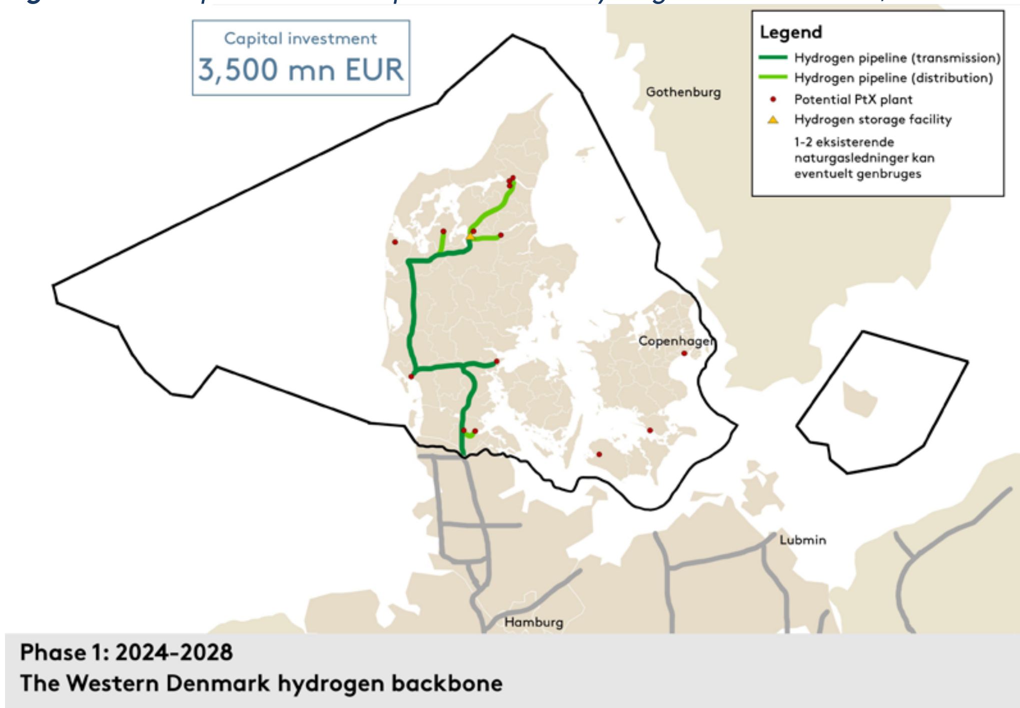
The capital investment requirement for the CIP Foundation's development plan is approximately EUR 3 billion and involves expansion of the onshore hydrogen pipeline infrastructure in Jutland. The backbone of the onshore hydrogen infrastructure runs from the German border and in a northern direction towards Egtved and then via the western shore of Jutland to the possible storage facilities in the former gas cavern in Lille Torup. In order to contain the expected quantities in the event of a full expansion of the hydrogen production based on renewable energy options, this part of the infrastructure requires 48" hydrogen pipes. The remaining parts of the onshore hydrogen infrastructure ('distribution lines') are smaller and vary in size depending on the expected quantities.

The distribution of costs is as follows: 60% is directly derived from the establishment of the pipes whereas the remaining 40% is split between costs for reinforcement of the power grid and compression for pressurisation of the pipes. In terms of timeline, the need for compression will arise at a later point when the capacity of the infrastructure is utilised to a higher degree. Even though the investment element, which is to ensure pressurisation, timewise belongs to this period, it is possible to defer this investment element and consequently the need for investment of EUR 0.73 billion until the need arises in a subsequent period.

POSSIBLE ADDITIONAL INVESTMENTS IN THE FIRST PHASE OF THE EXPANSION

The onshore hydrogen infrastructure whose dimensioning is proposed to fit the future need may function as a storage facility for Danish manufacturers in its own right as the capacity of the pipe will exceed demand in the first few years. Once the pipe achieves a high capacity utilisation rate, the compression may increase the capacity further. It is also possible to establish a storage facility in the salt caverns in Lille Torup. From a market point of view, this is not considered a necessity; however, other interests, such as in relation to security policy, may affect a decision such as this. Utilisation of the Lille Torup storage facility necessitates preparation of the storage facility which would entail an additional investment of EUR 0.67 billion.

***Figure 7.1:** First phase of the expansion of the hydrogen infrastructure, 2024-2028*



Source: COWI (2023b)

***Table 7.1:** Capital investment and operating costs related to the first phase of the hydrogen infrastructure, 2024-2028*

Investment element 2024 – 2028 (Phase I)	CAPEX, mn EUR for the period	OPEX, mn EUR pr. yr. fully built out
Transmission pipeline 48"/18 GW Southern Jutland, 186 Km.	570	12
Transmission pipeline 48"/18 GW Western Jutland-Ll. Torup, 180 km.	550	12
Distribution pipeline 4"-8"	190	6
Distribution pipeline 10"-18"	330	10
Distribution pipeline 20"-30"	370	11
Injected compressor	730	22
Electrical distribution, reinforcement of network	540	5
Total:	**3,280**	**78**

Source: COWI (2023b)

Table 7.2: Possible additional investments related to the first phase of the hydrogen infrastructure, 2024-2028

Possible additional investments in Phase 1, 2024-2028	CAPEX, mn EUR for the period	OPEX, mn EUR pr. yr.
Storage facility in Lille Torup 3 salt caverns	670	25

Source: COWI (2023b)

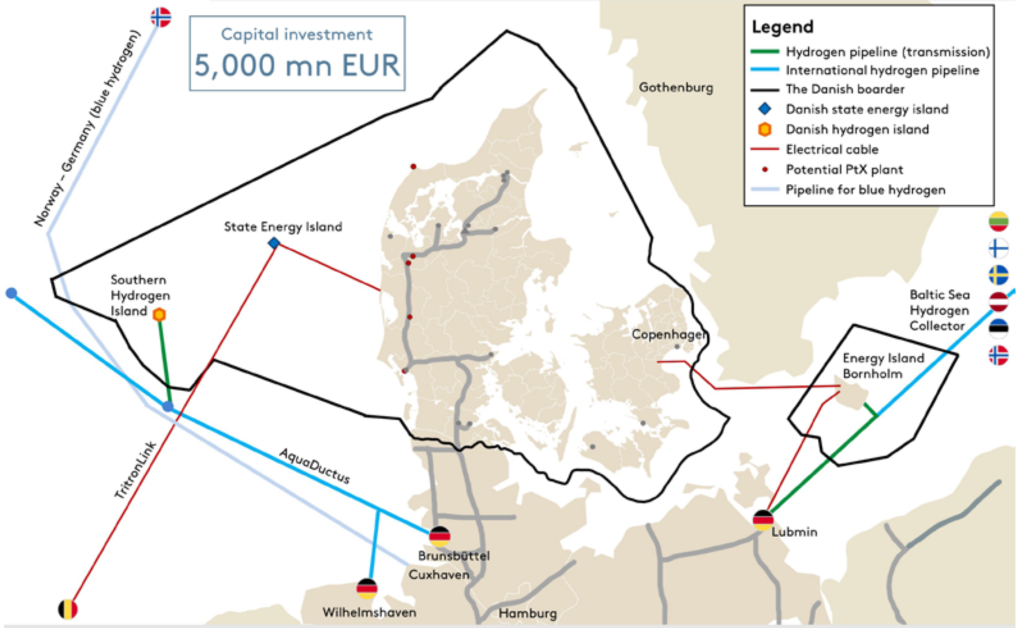
7.2. Need for investments during the second phase 2029-2035 – construction of energy islands and one hydrogen island

During the second phase of the CIP Foundation's development plan, the need for investment is split between the activities in the North Sea and Bornholm and amounts to approximately EUR 5 billion in terms of capital investment. The construction of the first hydrogen island, the Southern Hydrogen Island at Dogger Bank, involves the largest capital investment of EUR 2.5 billion. The distribution of the capital investment of phase II is approximately three-fourths in the North Sea and one-fourth in the vicinity of Bornholm.

Whereas the infrastructure expansion in the North Sea is proposed by the CIP Foundation, the infrastructure expansion in the vicinity of Bornholm has been proposed by another party. The CIP Foundation recommends that the hydrogen infrastructure from Bornholm to Lubmin is realised and utilised for the export of green hydrogen, which is the reason why is has been included in the investment overview and total costs.

OTHER INVESTMENT OPTIONS FOR PHASE 2 (2029-2035)
Several alternative interconnections and dimensioning options are described for the second phase. For instance, the Southern Hydrogen Island may be connected directly to the German mainland in Brunsbüttel if AquaDuctus does not become a reality. This entails an increase in costs of nearly 400% from barely EUR 0.4 billion to more than EUR 1.47 billion. In other words, the cost may increase significantly if an interconnection onto the shore is necessary; consequently, the realisation of international projects such as AquaDuctus may be central to the financial aspects of the infrastructure. In regard to the development plan, a dimensioning of 48" is recommended for the pipe between AquaDuctus and the Southern Hydrogen Island. Alternatively, the dimensioning could be reduced to 36". That would nearly halve the capacity of the pipeline, and the costs would be reduced by approximately 20%. Due to the expected quantities for transmission via this pipe, a 48" dimensioning is necessary; this only involves a relatively small additional investment compared to the increase in capacity.

Figure 7.2: Second expansion phase of the hydrogen infrastructure, 2029-2035



Phase 2: 2029-2035
Expansion of the Danish hydrogen infrastructure offshore and abroad

Source: COWI (2023b)

Table 7.3: Capital investment and operating costs related to the second phase of the hydrogen infrastructure, 2029-2035

Investment element 2029-2035 (Phase II)	CAPEX, mn EUR	OPEX, mn EUR	
Southern Hydrogen Island (15 GW)	2,500	50	The North Sea
Transmission pipeline 48"/18 GW Offshore, Southern Hydrogen Island – AquaDuctus (84 km.)	390	9	The North Sea
Offshore compressor station Southern Hydrogen Island – AquaDuctus	730	22	The North Sea
Total investment for the North Sea	**3,620**	**81**	The North Sea
Transmission pipeline 36"/10 GW Offshore, Bornholm – Lubmin (162 km.)	610	14	Bornholm
Offshore compressor station	730	22	Bornholm
Total investment for Bornholm	**1,340**	**36**	Bornholm
Total investment for Phase II	**4,960**	**117**	

Source: COWI (2023b)

Table 7.4: Possible alternatives related to the second phase of the hydrogen infrastructure, 2029-2035

Alternative investment elements, 2029 - 2035	CAPEX, mn EUR (Entire period)	OPEX, mn EUR (Annual expense at full built out)
Transmission pipeline 48"/18 GW Southern Hydrogen Island – Brunsbüttel, Germany (325 km).	1,500	33
Transmission pipeline 36"/10 GW Southern Hydrogen Island – Brunsbüttel, Germany (325 km).	1,240	28
Transmission pipeline 36"/10 GW Offshore, Brintø Syd – AquaDuctus (84 km.)	320	7

Source: COWI (2023b)

7.3. The need for investment during the third phase, 2036-2045 – Construction of the next hydrogen island and related interconnections

The third phase of the CIP Foundation's development plan for 2036-2045 involves a capital investment of approximately EUR 9 billion. In this phase another hydrogen island is added, and compressor stations are constructed in order to increase the capacity of the hydrogen infrastructure by means of increased pressurisation.

In this case, the investment need is split between the offshore activities in the North Sea and onshore. The capital investment for the construction of the Northern Hydrogen Island constitutes EUR 3.5 billion, and the costs will be split with about 90% for offshore projects and 10% for onshore activities. A large part of the investment need is earmarked for the amalgamation of the infrastructure which provides more transmission options for the hydrogen islands as well as the onshore production. The amalgamation includes electrical interconnections between the three islands which offer the possibility of transmission of electricity to Denmark, Germany and Belgium; similarly, the hydrogen interconnection to the Northern Hydrogen Island offers the possibility of balancing the hydrogen infrastructure during peak periods in the North Sea and onshore, respectively.

The economies of scope of a connection could be valuable as they facilitate switches between production of hydrogen and electricity, respectively, according to demand and wind conditions; moreover, the islands are able to export electricity to several markets if it proves beneficial.

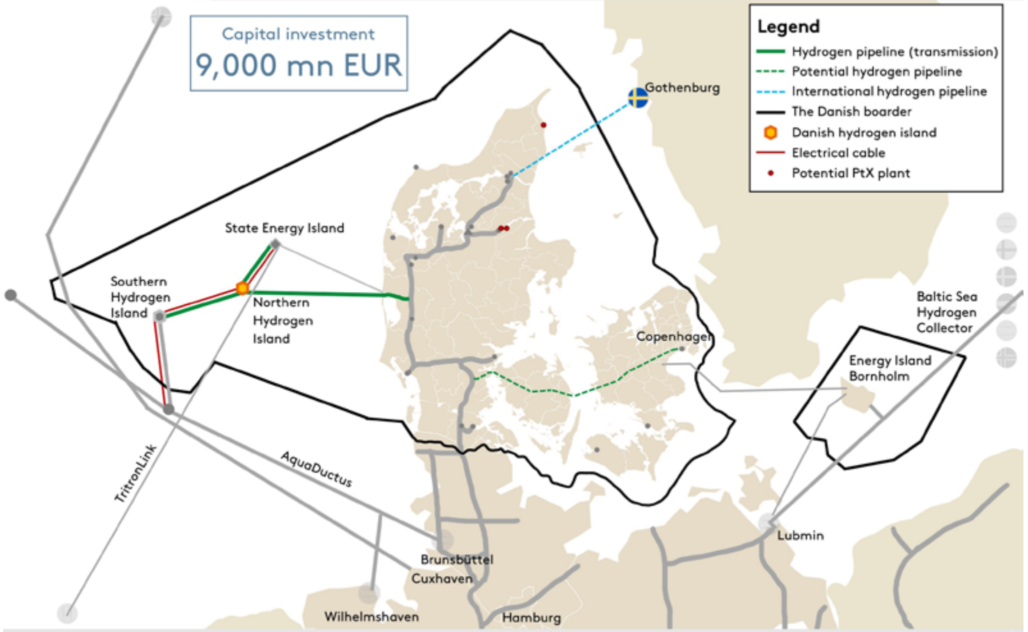
The internal electricity pipelines are not necessary for the infrastructure and the realisation of the hydrogen potential. However, they may be profitable investments as the utilisation rate of the produced energy may be increased.

Table 7.5: Costs related to the third phase of hydrogen infrastructure, 2036-2045

Investment element 2036 – 2045 (Phase III)	CAPEX, mn EUR (Entire period)	OPEX, mn EUR (Annual expense at full built out)	
Northern Hydrogen Island (15 GW)	3,560	70	Offshore
Electrical cable Northern Hydrogen Island – Southern Hydrogen Island	650	7	Offshore
Electrical cable Northern Hydrogen Island – State Energy Island	610	7	Offshore
Electrical cable Southern Hydrogen Island – AquaDuctus	700	7	Offshore
Transmission pipeline 48"/18 GW Northern Hydrogen Island – Denmark (128 km).	590	13	Offshore
Offshore compressor station Northern Hydrogen Island - Denmark	730	22	Offshore
Transmission pipeline 36"/10 GW Southern Hydrogen Island – Northern Hydrogen Island (78 km.)	290	7	Offshore
Offshore compressor station Southern Hydrogen Island – Northern Hydrogen Island	730	22	Offshore
Transmission pipeline 36"/10 GW Northern Hydrogen Island – State Energy Island (53 km.)	200	4	Offshore
Transmission pipeline 48" /18 GW (33 km.) Western coast of Denmark – Wester Denmark Hydrogen Backbone	110	2	Onshore
Compressor Station 10 GW, Western coast of Denmark	730	22	Onshore
Total	**8,900**	**183**	

Source: COWI (2023b)

***Figure 7.3:** Third phase of the expansion of the hydrogen infrastructure, 2036-2045*



Phase 3: 2036-2045
Scalling up production, multiple connections and balancing network

Source: COWI (2023b)

OTHER INVESTMENT OPTIONS FOR PHASE III (2036-2045)
Dedicated hydrogen production on the energy island enacted by the Government may therefore also lead to a hydrogen infrastructure directly to the shore. If the pipe is dimensioned at 36”, the estimated construction costs will constitute EUR 4.1 billion. Generally, such an interconnection is not recommended in the CIP Foundation’s development plan as the Northern Hydrogen Island, in terms of timeline, will be constructed before available renewable energy capacity is expected on the energy island and consequently dedicated electrolysis on the island is not justifiable.

With a power line between the Northern Hydrogen Island and the energy island, the latter will be able to utilise the excess power from the start and until it is profitable to establish electrolysis on the energy island. At that point in time, the Northern Hydrogen Island already has an over-dimensioned hydrogen pipeline to the shore which the energy island can connect to according to the development plan. As a result of the shorter distance, the costs of this pipeline are only about half the costs of a pipeline directly onto the shore.

If a hydrogen pipeline across Denmark is established, it would necessitate a capital investment of EUR 0.84 billion if the dimensioning is 16”. At the moment, it is unclear whether such a pipeline is needed; however, as the potential quantities for transmission are relatively low, a similar dimensioning could possibly suffice.

***Table 7.6:** Possible alternatives related to the third phase of the hydrogen infrastructure, 2036-2045*

Alternatives and extra investment elements, 2036 – 2045 (Phase III)	CAPEX, mn EUR	OPEX, mn EUR	
Transmission pipeline 36”/10 GW State Energy Island – Denmark (110 km.)	410	9	Alternative
Transmission pipeline 16” /1,5 GW Central Zealand	840	25	Extra investment

Source: COWI (2023b)

7.4. The overall need for investment in hydrogen infrastructure 2028-2045

The CIP Foundation proposes an expansion of the hydrogen infrastructure at a total amount of approximately EUR 17.5 billion. This concerns a little more than two-thirds of the establishment of the infrastructure in the North Sea whereas the remaining parts relate to the transmission of hydrogen produced onshore based on onshore or nearshore renewable energy. This corresponds roughly to the distribution of the produced quantities of hydrogen.

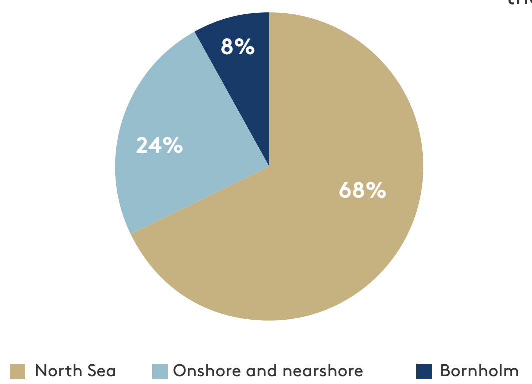
In comparison, the construction budget of the Fehmarn Belt is EUR 7 billion (in 2015 prices) whereas the total costs of the Great Belt Bridge were EUR 2.85 billion (in 1988 prices).

When comparing the capital investment in the hydrogen infrastructure with other types of energy infrastructure, the stages of the hydrogen infrastructure do not differ significantly from, e.g., expansions of the power grid.

From 2022 to 2027, Energinet expects to invest EUR 3.33 billion in the Danish power transmission grid. Add to this investments in the power distribution grid which leading to 2030 will cost the power grid companies between EUR 5.47 billion and EUR 8.27 billion. In other words, in terms of timeline and scope, Energinet's expected investments roughly match those proposed by the CIP Foundation for the first phase of the development plan.

The CIP Foundation's proposed hydrogen infrastructure will involve the largest capital investment in Danish history. The investment will be made over a period of 15 to 20 years, during which a transition of the energy system is to be carried out in order to deliver on the climate targets. The investment should be seen in the light of the significant export potential of EUR 13.5 billion annually which could help finance the welfare society in the future. Over time, hydrogen as the balancing element and relief of the power grid also reduces the need to expand the power grid as the electrification increases.

***Figure 7.4:** Distribution of the total capital investment in hydrogen infrastructure in the period 2028-2045*



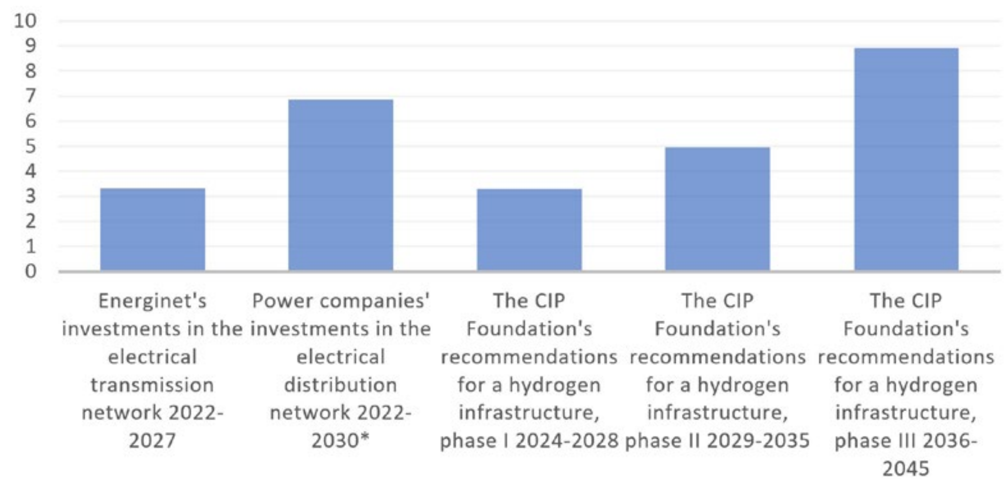
Source: COWI (2023b)

***Table 7.7:** Total capital investment in hydrogen infrastructure in 2028-2045 and annual operating costs at full implementation*

Total investment need		
Phase	**CAPEX, mn EUR (total period)**	**OPEX, mn EUR pr. yr.**
Phase I 2024-2028	**3,280**	**78**
Phase II 2029-2035	**4,960**	**117**
Phase III 2036-2045	**8,900**	**183**
Total:	**17,140**	**378**

Source: COWI (2023b)

***Figure 7.5:** Comparison of investments in energy infrastructure, bn EUR*



Source: Energinet (2022) og COWI(2023b)

CIP fonden

The risk of establishing a hydrogen infrastructure

Chapter 8

8.1. Numerous and diverse risks are involved in the establishment of infrastructure

Large infrastructure projects obviously involve a wide range of risks and the time frame presents an evident risk factor when it comes to a green hydrogen infrastructure as the expected future market demand, and therefore the dimensioning of the infrastructure needs to be considered long before the market matures. The capital investment is considerable with costs decreasing during the start-up phase and with a fairly high degree of certainty whereas the benefits materialise over a longer period of time and with a higher degree of certainty. The Government can support this type of risk transfer over time in order to realise the associated impact on the climate, see Chapter 9.

The demand for green hydrogen may be promoted via a range of political decisions and decarbonisation requirements (see Chapter 1) which in various ways will drive up the price of fossil alternatives and make green hydrogen more competitive, relatively speaking. In this case, the risk element is how the follow-up, and the implementation of the political targets proceed in practise. Also, whether regulation measures for the future hydrogen market are developed in due time.

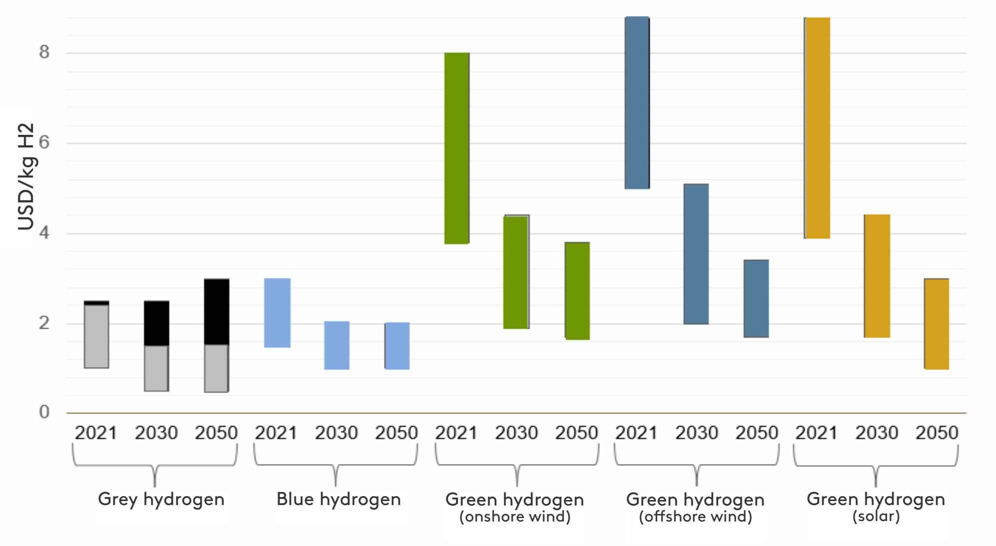
The price of green hydrogen depends in particular on the price of renewable energy which constitutes the basis of the production

***Box 8.1:** The price of green hydrogen and the expected development*

According to COWI, the price of green hydrogen is approximately USD 3-6 per kilo whereas fossil-based hydrogen is just USD 1.8 per kilo. If the fossil hydrogen has been climate neutralised through CCS and takes the form of blue hydrogen, the price is approximately USD 2.3 per kilo. Prices vary geographically as the most expedient transmission method for hydrogen (regardless of colour) is via pipes and is therefore typically used for a limited regional market.

There are many forecasts for the possible price trend and when green hydrogen can compete with grey hydrogen in terms of price. Axcelfuture expects this to happen at some point after 2030, whereas the International Renewable Energy Agency (IRENA) expects green hydrogen to become internationally competitive at a price of approximately USD 2 per kilo leading up to 2030. The IEA has come to the same conclusion and predicts that the price of green hydrogen based on solar energy may drop to USD 1.5 per kilo in 2030 whereas green hydrogen based on offshore wind may decrease to USD 1.75 per kilo; this would place it in a price range which would facilitate competition with grey and blue hydrogen in some cases. Green hydrogen produced within Danish territory is at the bottom of the cost estimate.
Sources: COWI, Axelfuture (2023), IRENA (2021) and IEA (2022)

***Figure 8.1:** The expected price trend for hydrogen by energy types from which hydrogen is produced*

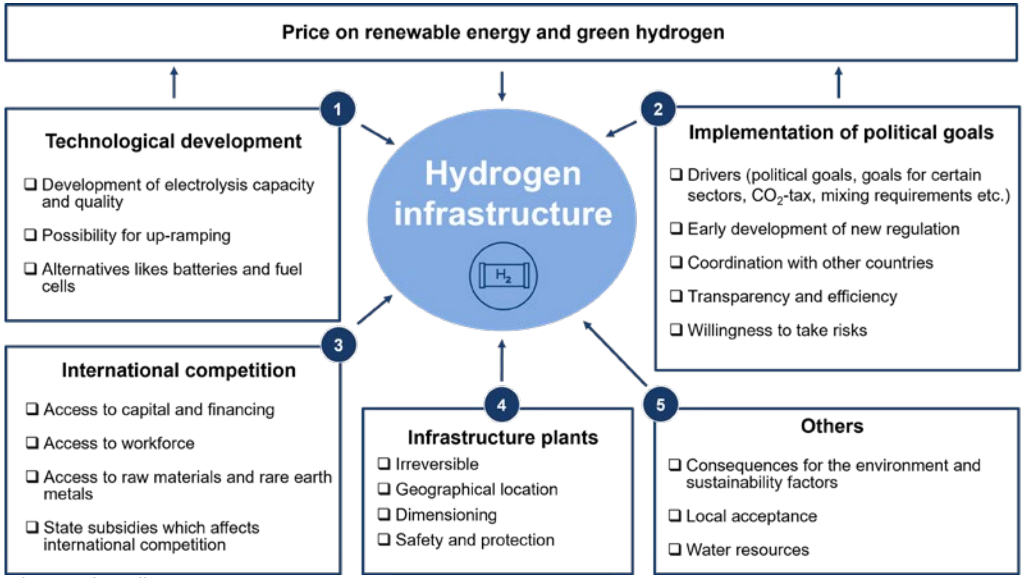


Source: IEA (2022)

as well as the price of the electrolysis technology behind. Add to this the cost of transmission via the relevant hydrogen infrastructure. However, the establishment of a hydrogen infrastructure is associated with other risk elements. The international competition for, e.g., capital, labour and raw materials will be intense, not only for the hydrogen market but for a wide range of other elements of the green transition, such as sourcing of sufficient quantities of renewable energy.

The establishment of infrastructure also involves risks related to planning and the subsequent operation and security. Add to this issues in the construction phase in relation to possible environmental issues and local acceptance. See Figure 8.2 for an overview of possible risk elements related to the establishment of the hydrogen infrastructure with further elaboration and discussion throughout the chapter of mitigating measures and possibilities for consolidation of the infrastructure decision.

***Figure 8.2:** Risk elements related to the development of the hydrogen infrastructure – fierce competition for the same resources and dependency on political drivers*



Source: Own illustration

8.2. The technological development must support a substantial scale-up

The future hydrogen market depends on continued technological development of the underlying electrolysis capacity and the electrolysis quality which may contribute to reducing the costs of utilising the technology and make it relevant for large-scale operation. The price of electrolysis has decreased by 60% since 2010, and IEA (2022) expects the price to decrease by an additional 70% leading up to 2030.

EUROPE IS AMONG THE LEADING MANUFACTURERS OF ELECTROLYSIS CAPACITY

The development is driven by a certain geographical diversity, in particular for Europe, the US and China, with 13 of the 20 largest developers currently being located in Europe, including two in Denmark, see Figure 8.3.

Even as the development of the technology behind electrolysis will result in decreased costs over time, the production costs account for the lion's share of the price of green power, according to IRENA (2021).

Meanwhile, it is important that the technology behind electrolysis is developed to be able to utilise water with a lesser degree of purity as compared to today when only potable water reserves typically meet the electrolysis requirements. Otherwise, the global need for green hydrogen will also put pressure on potable water resources.

NEED FOR A SCALE-UP OF ELECTROLYSIS PRODUCTION

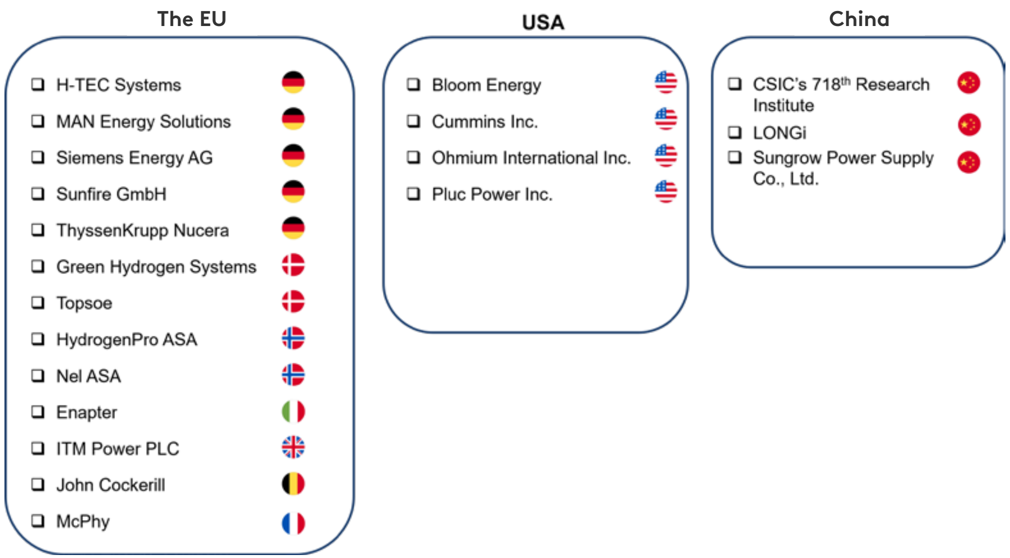
The largest technological advancement will be a sufficient scale up production and the installation of electrolysis (up-ramping) in accordance with the significant demand which is also expected within a relatively narrow time frame.

Consequently, this is also about optimisation of the production and logistics. Please refer to, for instance, Chapter 2 on the requirements for installation of electrolysis capacity in order to deliver on the political targets.

When new forms of energy and the related energy infrastructure are expanded, which involves significant investments and installations of an irreversible nature and will affect the market in many years to come, the costs and the risk profile of possible alternatives must be taken into consideration.

The Danish Council on Climate Change (2023) points out that battery storage, fuel cells or other means of storage (such as thermal), which is also a field with massive technological advances, may constitute alternatives in terms of balancing (storage of electricity in periods of maximum production of renewable energy which is then adapted to the demand for power for direct electrification). Furthermore, several of these solutions will most likely be used at the same time. However, not many alternatives to hydrogen (and Power-to-X products) exist[1] when it comes to energy for energy intensive industrial processes and heavy transport which is also included in the decarbonisation targets. Therefore, a greater mix of energy types and technologies will be used in the future, with hydrogen playing a major role.

***Figure 8.3:** The 20 largest manufacturers of electrolysis capacity are located in Europe, China and the US*



Source: Blackridge Research and Consulting (2023): Global Top 20 Hydrogen Electrolyzer Manufacturers, 31 March 2023

1 Green technologies also include the expansion of smaller, nuclear-powered facilities and development of fusion energy; however, the required development and establishment in order to facilitate operation on a commercial scale is not expected to happen in time to drive the green transition.

8.3. Political targets should be followed up by implementation and transparent, seamless processes

As mentioned above, there is no lack of great political ambitions for the decarbonisation of society, including relevant targets, sector requirements, carbon taxes, entrainment requirements etc. at national as well as EU level. This requires various degrees of specification and implementation plans and there is an obvious need for credible follow-up on and realisation of the targets.

As the consequences and costs of the green transition become evident, in the form of increased energy prices etc., criticism and political pressure may surface to ease the targets, changes of the implementation etc. The criticism was evident in, for instance, France in 2018 when 'the yellow jackets' protested against the increasing fuel prices (higher taxes on fossil fuels) and the distributional effects of this.

Therefore, to follow through on the ambitions and to point out the necessary measures in order to realise the targets carry a political risk. Conversely, a lot of political capital is tied to the targets and consequences – at human, geographical and economic level – of the climate crisis, and the global warming is so significant that action is imperative. It is an ongoing process to explain and show the correlation between the climate measures and the consequences of not implementing them.

FAILURE TO DEVELOP REGULATORY MEASURES IN DUE TIME WILL ENTAIL INCREASED RISKS AND COSTS

The quick expansion and transition which the political targets and declarations call for also requires a similarly swift development of regulatory measures and framework conditions so the market players know the conditions under which they are required to operate. As described in Chapter 5, various countries are competing for the same resources, and failure to develop regulatory measures and frameworks in due time will on the other hand render the transition more costly due to an increased level of risks or have the consequence that the expansion is not completed at all.

One element of the timely development of regulatory measures involves transparent procedures and schedules so the market players are aware of the requirements they must meet and are able to plan according to the length of the administrative processing time and the nature of approval processes they can expect. Otherwise, the costs of the expansion plans will increase further. The intention of the EU's Green Deal Industrial Plan of February 2023 was a predictable and simplified regulatory approach at European level to the necessary investments in the green transition which is to include fast-track permissions, deadlines for administrative processes, simplified approval processes (with one-stop shop procedures for vital technologies such as wind and solar energy) and support the gradual development of regulatory measures as described in Chapter 2.

This means that some processes will be running concurrently and with some overlaps instead of successively in order to cut the overall length of the administrative processes with the risk that the approval process has been in vain if a project is stopped by another approval process. In March 2023, a new energy crisis team, NEKST, was set up in Denmark and tasked with handling the practical and cross-cutting coordination between various authorities in relation to energy political challenges such as the phase-out of gas, the implementation of district heating and facilitating the construction of plants for the production of renewable energy.

POLITICAL TARGETS FOR THE EXPANSION OF RENEWABLE ENERGY NECESSITATE EXPORTS; IS THE GOVERNMENT READY TO TAKE ON THIS RISK?

Finally, there is the question of the possible risk-taking of the public sector and the co-financing of the hydrogen infrastructure. The hydrogen infrastructure differs from other types of energy supply in Denmark in that its main purpose is to cater to the energy demand and security needs of Denmark's closest neighbours via exports and only to the national demand and reliability of supply to a lesser degree. Production of hydrogen is required as the political targets for the production of renewable energy greatly exceeds the domestic demand and to a degree that renders Denmark's national power grid and the power grids of the country's closest neighbouring countries unable to receive the renewable energy without major updates to the national power grids.

Therefore, when it comes to the expansion and dimensioning of the hydrogen infrastructure it needs to be clarified to which degree commercial business models and an emerging market are compatible with a political call for expansion of renewable energy and the need for mitigation of the risk during the initial phase as described in Chapter 5.

8.4. Fierce international competition for the same input factors

When building a hydrogen infrastructure and the associated energy and hydrogen/PtX production, a number of resources are needed for which the competition is fierce – not only in Denmark and in relation to Denmark's closest neighbouring countries but also internationally within the EU and globally.

HUGE NEED FOR FINANCING AND AVAILABLE GREEN CAPITAL – NOW IT IS TIME TO MAKE THE ENDS MEET

The need for investments in relation to the green transition is vast and this means that the access to capital and various financing models may prove to be a limiting factor. In the assessment of the Climate Partnership for the Financial Sector (2020), the Danish target of 70% alone requires investments of EUR 80 billion of which a major part will be allocated to the expansion of renewable energy. The CIP Foundation's proposal for establishment of a cohesive hydrogen infrastructure entails a capital investment of approximately EUR 17.5 billion over the next two decades.

The green capital seems to be available; consequently, the challenging part is to channel it to projects through financing models relevant to private players. The financing must fit the risk and the repayment profile of the projects. It may be necessary to expand the knowledge of the financing mechanisms and have the conditions 'adapted' to match the green projects in dialogue with experts.

As early as 2019, the Danish pension funds undertook to invest DKK 350 billion (USD 55 billion) in renewable energy, and subsequently at COP 26 pension funds in the Nordic countries and the UK pledged to invest a total of DKK 835 billion (USD 130 billion) in the green transition. Green investments are also a focal point in other parts of the financial sector, including private equity funds and private venture capital, targeted at the growth stages, as commercial projects in high demand.

In Denmark, the Government supports the green transition through, for example, the Export and Investment Fund of Denmark (EIFO), which offers green risk capital in addition to export credit financing.

At the Green Marienborg Meeting on 19 April 2023, a proposal was made to the effect that going forward, the mortgage-credit institutions should be able to co-finance offshore wind farms further away from the shore with an estimated financing need suitable for mortgaging in excess of EUR 26.7 billion, according to the Ministry of Industry, Business and Financial Affairs.

As it appears from Chapter 2, the European Union is very focused on risk capital and means to channel funds to the relevant investments in a more expedient way as a supplement to possible research and development subsidies, for instance through the European Hydrogen Bank. Furthermore, the European Commission has encouraged the European Sovereignty Fund to invest in R&D and specific industrial projects, and the best channelling of funds is now being considered.

COMPETITION FOR LABOUR FOR THE GREEN TRANSITION

The need for labour to support the green transition has been a challenge for quite some time. It is hardly news as it is a result of the expansion of the hydrogen infrastructure and the production of hydrogen/PtX. Establishment of renewable energy in the form of solar parks, wind turbines etc. requires labour with various skill sets. Highly specialised qualifications with know-how of electrolysis etc. will become an extremely scarce resource, particularly initially when the technology and scaling are being established whereas other fields are in need of, for instance, skilled labour which is also relevant to other sectors. For instance, for some of the sections, the labour used for the construction of oil rigs and the labour used for offshore wind farms does not differ much.

The demand for the necessary labour is local for specific facilities but also highly international as there are plans for the establishment of hydrogen infrastructure across a number of different countries at more or less the same time. HBS Economics (2022) has analysed the situation in Denmark and the number of job postings requesting green qualifications and emphasises in particular the need for more skilled labour with a background in the iron and steel industry, construction, engineering, agriculture and fishery, etc. However, there is also a need for people with university degrees in engineering and in some instances even social sciences. See also the Ministry of Industry, Business and Financial Affairs (2023) for a description of labour needed for the green transition.

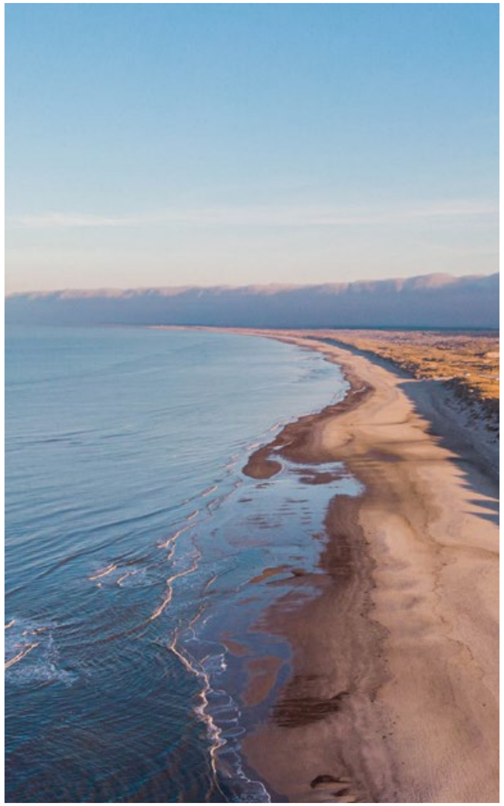
Fierce international competition for the same labour over a limited number of years makes it difficult to educate, retrain and upgrade the skills of the workforce which, all things considered, may lead to an increase in wages and higher costs for the expansion.

The more the planning and the time frame can be clarified and communicated regarding the various phases and expansion stages of the hydrogen infrastructure, the greater the possibility is for planning an upgrade and for

the labour to move according to the recent demand and offering the right qualifications. The value of early planning and communication also rubs off on the other resources needed when establishing the infrastructure.

WIND TURBINES AND SOLAR PANELS REQUIRE RARE METALS ONLY AVAILABE IN FEW PLACES AND THROUGH COMPLICATED SUPPLY CHAINS

The green transition, including the future hydrogen production, the infrastructure and the expansion of renewable energy, also requires access to raw materials and rare metals in sufficient quantities. Not only materials such as glass fibre, concrete and steel that first come to mind when you think of wind turbines, but also various rare earth materials



needed when various forms of renewable energy are to be expanded[2]. This becomes even more challenging as the presence of these rare and critical raw materials is concentrated in very few countries. In 2022, the global stock of rare earth materials for extraction were estimated at 130 million tons, with China, Russia, Vietnam and Brazil accounting for 80%, according to Økolariet, a Science and Edutainment Centre. Consequently, the EU has made regulations on critical raw materials (March 2023)[3] which facilitate the recycling of raw materials and are intended to enhance the European capacity and reduce the dependency on imports from a handful of individual countries.

Recent finds of large quantities of rare earth metals in northern Sweden support the green transition in Europe and offer a greater autonomy in the long term; however, according to the Danish Center for Minerals and Materials (MiMa)[4] under the Geological Survey of Denmark and Greenland (GEUS), the challenge is that China dominates the technologies and enterprises used for the processing of the raw materials from the moment they are extracted from the ground until they can be used as input products. It is necessary to make the supply chains more reliable.

THE COMPETITION FOR STEEL FOR THE GREEN TRANSITION INCREASES THE PRESSURE FOR DECISIONS

It could prove challenging to acquire enough steel for the production of hydrogen pipes alone. Particularly, if the steel is to be green which, for instance, requires green hydrogen. There are relatively few manufacturers of hydrogen pipes; however, as appears from Chapter 2, a large number of different European projects will be running more or less in parallel up to 2030 alone for which new or retrofitted pipes are required.

The great demand makes it imperative to order well ahead and with financing guaranteed, which again only intensifies the challenges of lack of coordination of the timeline between various types of decisions (inconsistent timeline) as described in Chapter 5. If parts of the Danish hydrogen infrastructure is to be completed by 2028, the orders for steel pipes must be placed in the foreseeable future. If decisions on infrastructure are made at a later point in time, the delivery time of the hydrogen pipes will dictate when commissioning is possible.

SUPPORTING PORT INFRASTRUCTURE MAY ALSO FACE CAPACITY CHALLENGES

Whether it is for the expansion of renewable energy, hydrogen infrastructure or hydrogen production, relevant and available port facilities are often a scarce resource as part of inbound and outbound sea freight of the necessary elements and components. In regard to activities in the North Sea or the Baltic Sea, Danish ports compete with foreign as well as domestic ports to provide the necessary facilities, capacity, depth etc. Available square meters at the port area are also in high demand for the establishment of hydrogen, PtX production etc. Going forward, a more coordinated approach when offering the necessary facilities could prove beneficial.

THE RISK OF BOTTLENECK SITUATIONS IS INCREASED BY POLITICAL TARGETS WITH FINAL DEADLINES

The timing of the expansion is complicated by the fact that nearly all countries have set climate targets that need to be realised more or less at the same time at various locations around the world. In the EU alone, a large number of projects are to be completed at more or less the same time around 2030, which also increases the risk of bottleneck situations during the construction phase.

Time becomes a scarce resource which puts the market development under pressure when a lot of political capital is tied to certain targets being met by certain years. This also adds value to timely planning of the infrastructure supporting the expansion of the renewable energy.

GOVERNMENT GRANTS MAY CAUSE DEVELOPMENT AND PRODUCTION TO MOVE

A limited period of time for the development combined with a limited number of market players globally equal an increased focus on the parties with the most transparent development plans with supporting framework conditions.

As an example, the US has made the choice to provide government grants for the production of hydrogen and PtX products as part of the Inflation Reduction Act. In some instances, the state grants may give the hydrogen a competitive advantage in Europe despite the costly transmission and furthermore help move the market interest to the US for a number of years while a new technology is developed. See the CIP Foundation's Market Assessment (2023).

In response, the EU has worked on shorter administrative processes and improved the access to green financing, among other things, via the Green Deal Industrial Policy.

Efficient processes, clearly defined time schedules, coordinated planning of the infrastructure and other forms of de-risking are competitive parameters which the States – apart from direct subsidies – can also use to affect the market interest.

2 See, for instance, MiMa (2021) on rare earth metals and supply chains. Approximately 1 ton of rare earth materials is used for the production of one large wind turbine, according to Økolariet.
3 See, for instance, the EU Commission's fact sheet on European Critical Raw Materials Act (europa.eu)
4 DR interview with Per Kalvig, Emeritus, Department of Mapping and Mineral Resources, 12 January 2023.

8.5. Planning and construction of infrastructure also pose inherent risks

Hydrogen infrastructure involves a capital investment of a significant and irreversible scope once the pipes have been embedded in the ground or placed on the seabed. At this stage, the infrastructure can no longer be moved or transmit more than allowed by its dimensions[5]. This requires meticulous planning and selection of the best geographical locations making allowance for alternative applications of the area as well as selection of the most obvious and cost-effective transport distances between the production site and the buyers' location.

DIMENSIONING FOR FUTURE NEEDS IS OBVIOUSLY SUBJECT TO UNCERTAINTY

In order to optimise the demand-side and the needs of market players and minimise the risk of planning errors, the relevant parties should be included in the planning of the common part of the infrastructure and also share the financial responsibility for the selected parameters.

As dimensioning for the future and the potential transmission needs are to be taken into consideration at the same time, the Government may use its knowledge of areas planned for renewable energy in the future and the future need for direct electrification in Denmark and abroad via existing and planned interconnections. In that case, it is possible to a certain degree to 'count backwards' and calculate the quantity of excess renewable energy available for production of hydrogen and the location of the energy while considering the quantities needed for direct reprocessing into PtX products.

The geographical location of the hydrogen infrastructure must match the locations of current and future manufacturers and buyers. When the parties select the location for production of hydrogen and possibly PtX, they take into consideration where large quantities of renewable energy (or potential renewable energy) are accessible, access to transmission and storage of hydrogen (hydrogen infrastructure), room for facilities, whether the power grid is sufficiently reliable, access to water and whether there is a near-by district heating network or other possible buyers of excess heat generated in connection with the electrolysis process.

In case of privately owned lines, the commercial parties carry the risk themselves of an unsuitable location or dimensioning compared to the need now and in the future.

ENERGY POLITICS HAVE TURNED INTO SECURITY POLITICS – ALSO AS REGARDS THE MONITORING OF INFRASTRUCTURE

In the light of the sabotage of Nord Stream I and II, more attention is now paid to monitoring and safeguarding of the energy infrastructure, including critical infrastructure in particular. This is relevant whether the energy infrastructure transmits power, natural gas and biogas or hydrogen. Furthermore, the need will probably be of a more permanent nature. Monitoring and safeguarding of the energy infrastructure has been a recurring theme of the negotiations for a Danish defence agreement, which were to start in May 2023, including increased defence budgets; moreover, security requirements for the market players are expected to be included in future calls for tenders regarding renewable energy and hydrogen infrastructure and the establishment of energy island constructions.

One way to make the expansion of the infrastructure more robust in regard to future needs is to carry out a staged expansion and in such a way that the individual stage does not depend directly on future stages but has a standalone functionality. To the extent possible, each stage must be based on a no-regret decision. This is also the underlying basis of the CIP Foundation's proposal for a hydrogen infrastructure.

5 To a certain degree, the dimensioning may be reinforced by means of increased pressurisation; however, this would entail recurring costs for compressor stations.

8.6. Other aspects affecting the expansion of the hydrogen market and infrastructure

CONSTRUCTION PROJECTS MAY AFFECT THE LOCAL ENVIRONMENT DURING THE CONSTRUCTION PHASE AND OCCASSIONALLY PERMANENTLY

When constructing large facilities, whether they relate to infrastructure, facilities for renewable energy or production plants for hydrogen and PtX, it could have environmental implications or lead to sustainability issues, whether temporarily or permanently. In this regard, regulation measures must be in place and require the necessary pre-investigation studies[6].

Denmark has gained a lot of positive experience from constructing the Great Belt Bridge, the Øresund Bridge and the Fehmarn Belt in ways that eliminate a negative impact on the environment via meticulous planning and mitigating measures such new stone reefs and establishment of new natural areas or substitute natural areas. These large construction projects include onshore as well as offshore installations, and the experience gained is transferable to hydrogen pipe infrastructure. This also applies to the lesson learnt from the establishment of the Baltic Pipe (the natural gas pipeline from Poland and across Denmark to the North Sea), where the gas pipe passes through three Natura 2000 areas, which are internationally protected natural areas[7]. This was carried out by means of controlled horizontal directional drilling to ensure that the project did not affect the vulnerable natural areas. At project level, the World Wildlife Fund and Ørsted have joined forces to restore vital marine eco-systems in synergy with the increased number of offshore wind projects via new reefs for oysters and northern horse mussels as part of the wind turbine foundations.

It should be considered whether it is feasible to combine some of the necessary substitute natural areas which may be required in connection with the local stages of the hydrogen infrastructure in order to achieve larger and more interconnected natural areas as compensation for replacement needs from the various stages of the hydrogen infrastructure.

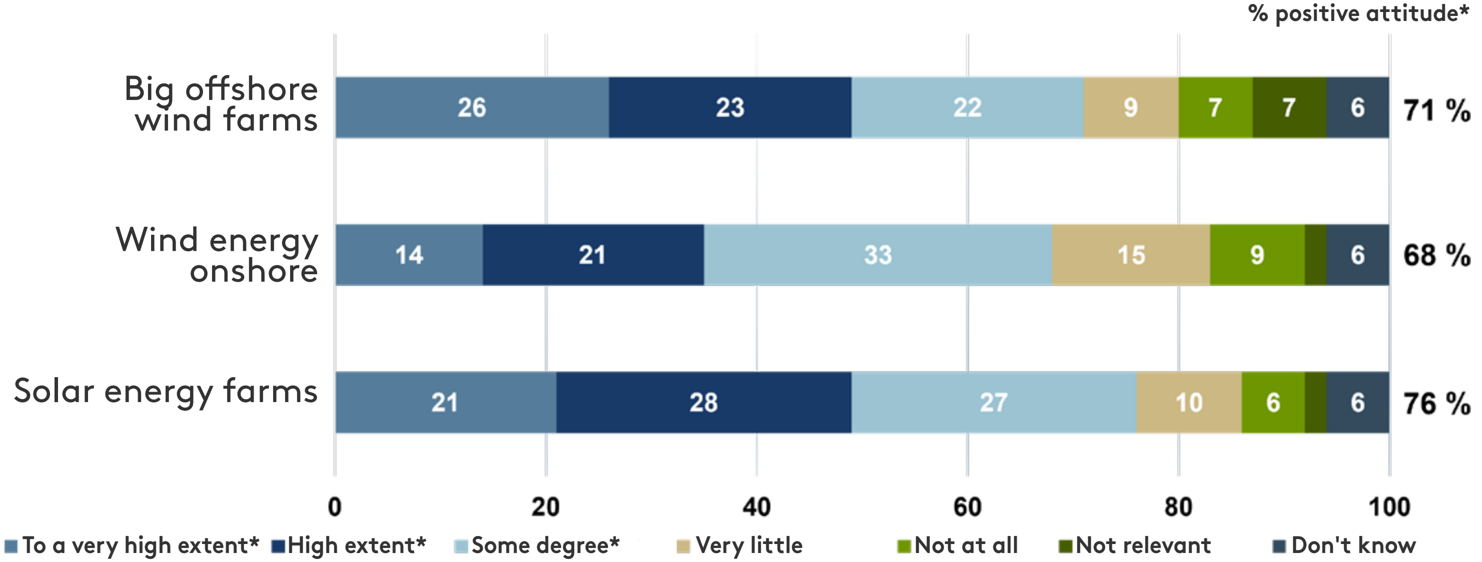
THE SUPPORT OF THE LOCAL POPULATION DEPENDS ON THE INTRICATE NATURE OF THE BENEFITS

The potential impact on the local environment is also an important factor when it comes to the local acceptance of the construction projects. The local understanding of the expansion is also affected by other aspects, such as the visual presentation and whether there is a correlation between those responsible locally for the external costs of the green facilities and those standing to gain from them.

In the event of local resistance, the expansion is delayed, and the costs increase accordingly. Generally speaking, the population comprehends and supports the green transition, and this support may have increased as a result of the war in Ukraine and the need for energy independence in Europe. In surveys published by Concito, Denmark's green think tank, more than two-thirds of the respondents reply that they to a very high degree, a high degree or to some degree are willing to accept large offshore wind farms in the vicinity of their home, and the acceptance is geographically valid across the country. This relatively strong support is seen across the various forms of renewable energy, see Figure 8.4.

Despite the strong support in general, the media are full of stories about local resistance, once the projects are realised ('not in my backyard', NIMBY). According to Eurowind Energy, it is exceptionally rare that onshore wind turbines or solar parks are installed without local protests[8].

***Figure 8.4:** The Danes' acceptance of renewable energy (installations) in the vicinity of their homes, 2022*



6 A strategic environmental impact assessment of the national plan for a hydrogen pipeline infrastructure must be prepared which lay down the framework for future planning permissions in order to incorporate environmental considerations and biodiversity conservation. At project level, an environmental impact assessment (EIA statement) is prepared before the project owner is granted a permission to start the specific stage of the hydrogen infrastructure.
7 Denmark has more than 250 designated Natura 2000 areas which in total constitute 9% of the Danish land area and 26% of the Danish marine area.
8 Altinget, 18 April 2023 "I Veddum Kær er det lykkedes at opstille 9 vindmøller og 18 fodboldbaner med solceller uden en eneste klage fra de lokale" (In Veddum Kær, 9 wind turbines and 18 football fields with solar panels were established without any local complaints at all).

Green Power Denmark emphasises local co-ownership as one of the keys to gain support[9] and a method to share the benefits with those directly affected.

With meticulous planning and the involvement of the local population, it is possible to establish a hydrogen infrastructure in Denmark where the perceived negative implications are handled by a combination of measures, such as offering the possibility to buy stakes in energy plants, establishment of new natural areas as replacement, recreational trails etc.

HYDROGEN IS BASED ON LARGE QUANTITIES OF HIGH QUALITY WATER

Finally, there is the fundamental fact that hydrogen is produced by splitting water. This means that – apart from power from renewable sources – sufficient quantities of water need to be accessible for the production of hydrogen.Onshore hydrogen production in Denmark may entail the use of potable water resources from the ground water which may prove challenging locally.

If the hydrogen production takes place in the vicinity of other enterprises, the possibilities of reusing water from various industrial processes should be considered ('symbioses'). DIN Forsyning in Esbjerg[10] is trying to replace ground water for two water intensive PtX plants by cleaned wastewater which would be a benefit in terms of sustainability as well as financially.

Alternatively, desalted sea water could be used. This is an energy-intensive process but could be a future approach for any hydrogen production on energy islands at sea and in coastal areas. Denmark's location is relatively advantageous compared to other countries with less coastline. The desalting can be supported by excess heat from the electrolysis process and from locally produced renewable energy. New research results indicate that electrolysis using sea water directly should be possible (Nature Energy, 2023), and this is already being tested at test facilities in, for instance, Germany. Development of the necessary qualities of the water used for electrolysis is one of the areas where the technology behind needs further development. This also applies to the technical lifetime of the plant.

9 Green Power Denmark, 4 January 2023: "LIV-modellen giver vedvarende energi et lokalt rygstød" (The LIV model ensures local support for renewable energy
10 Energy-supply.dk, 3 June 2022: "Renset spildevand skal gøre PtX endnu mere grøn" (Cleaned wastewater needs to make PtX even greener).

The benefits building a hydrogen infrastructure

Chapter 9

9.1. No large-scale green transition without hydrogen and PtX products

Green hydrogen and the associated hydrogen infrastructure is a necessary prerequisite for succeeding in the green transition.

It is not set in stone that Denmark is to lead the green transition and kick-start the hydrogen industry. However, Denmark is well-equipped to do so. From extensive experience with wind power to vast and cost-effective areas to production of renewable energy which greatly exceeds any future domestic consumption. Denmark is competitive in green hydrogen on the Northern European market, and as mentioned earlier some of Denmark's neighbouring countries have imports as a declared strategy, and the demand for imports exceeds by far the Danish hydrogen production capacity. Furthermore, Danish enterprises are among the top manufacturers of electrolysis.

This enables Denmark to take responsibility for the green transition and the European energy supply and security at international level during otherwise challenging times.

If Denmark is among the first to get started, the national renewable resources will not only be utilised expediently; Denmark will also create an international climate footprint which will be among the largest possible for Denmark and far greater than the footprint resulting from our current exports. Therefore, if the intentions are to make Denmark a pioneer country in terms of the green transition, this is the chance. Meanwhile, Denmark is generating knowledge, creating innovation and gaining experience which may be used to distribute the technology in large parts of the world. Add to this the resulting activity and creation of local well-paid and productive jobs in areas of Denmark which are outside the major cities and not necessarily already characterised by economic activity.

See Table 9.1 for a list of societal benefits from the establishment of hydrogen production in Denmark with an associated hydrogen infrastructure.

9.2. Denmark could set a significant international climate footprint

With the potential for hydrogen production as described in the long-term development plan, Denmark may be able to set a sizeable climate footprint globally despite the humble size of the country.

The European Union has set a target that requires the member states to produce 10 million tons of green hydrogen by 2030. Denmark is able to deliver 0.5 million ton of green hydrogen despite being one of the smallest member states. Even at this point in time, the climate impact of Danish green hydrogen displacing grey hydrogen in other locations will exceed the climate impact in Denmark from, for instance, the carbon tax. See Box 9.1.

And in the long run, once Denmark's production of renewable energy and hydrogen has been expanded and reaches a level corresponding to the estimated expansion potential then green hydrogen produced in Denmark will have the potential to displace at least 70 million tons of CO2e or one-tenth of Germany's current climate emissions.

In other words, by means of green hydrogen Denmark will be able to play a positive role on the international climate stage which by far surpasses what Denmark could achieve through exports etc.

THE CLIMATE IMPACT OF GREEN HYDROGEN EXPORTS SURPASSES THE EFFECT OF GREEN ENERGY TECHNOLOGY EXPORTS

It is estimated that the climate impact of Danish exports of energy technology contributes to potential climate impact reductions of 5-8 tons of CO2e in other countries. This is, so to speak, Denmark's positive climate contribution to other countries.

The Danish Energy Agency expects 1 ton of green hydrogen to displace 11 tons of CO2e when green hydrogen displaces grey hydrogen, according to the Danish Ministry of Climate, Energy and Utilities (2023). As demonstrated by the CIP Foundation (2023), by 2030 the Danish hydrogen production will already constitute 19 TWh or approximately 0.5 ton of green hydrogen annually and thus cause a climate impact equivalent of 5 tons of CO2e, or more or less equivalent to the current energy technology exports.

Within a relatively narrow time frame and by means of modest hydrogen production, Denmark is able to contribute to a climate impact comparable to our energy technology exports which have been many years in the making and is an area in which Denmark considers itself as a pioneer country of sorts.

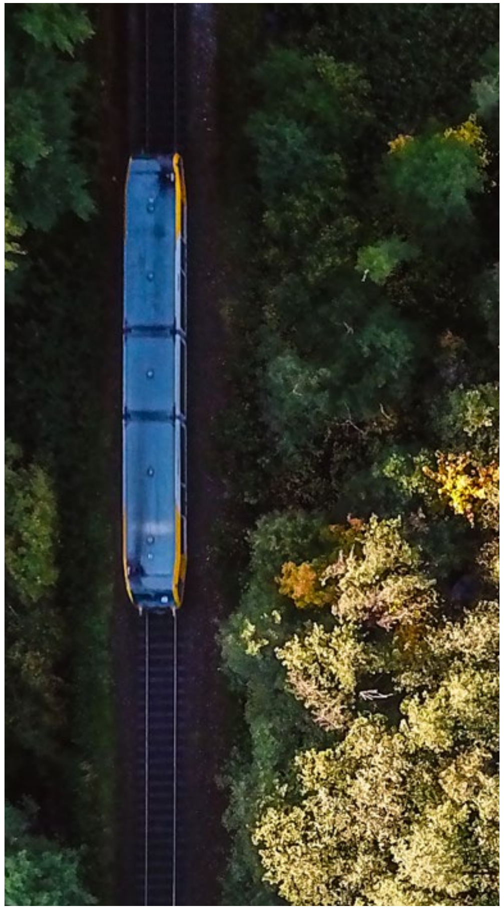


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***Table 9.1:** How society will benefit from the establishment of hydrogen production and hydrogen infrastructure*

	Effects	Elaboration
AT SOCIETAL LEVEL (permanent, structural effects)	European energy supply and security politics	Reduces the dependency on Russian gas (fossil-based) and supports a reliable supply of green energy.
	Large-scale green transition	Supports CO2e reductions equivalent to one-tenth of Germany's current emissions or more than 1.5 times Denmark's emissions on Danish soil.
	A necessary element in the green transition of energy-intensive industrial processes and long-distance heavy transport	Cannot be achieved through electrification or by means of biofuels (due to limited biomass), and therefore the green transition requires hydrogen and PtX products.
	Revenue based on renewable sources	Tax revenue from exports, direct and derived financial activity and employment.
	Lower but more fluctuating energy prices to the benefit of Danish enterprises and consumers	As a result of a massive expansion of renewable energy, more hours of cheaper energy are available for the benefit of enterprises and consumers with the option of consumption flexibility .
	Infrastructure as a common good	Economies of scale due to coordinated planning in the event of more users.
SOCIO-ECONOMIC FACTORS (temporary and partial effects)	Achievement of political targets (adopted by a broad majority of the members of the Danish parliament and government leaders from several of Denmark's neighbouring countries)	Hydrogen production and infrastructure are necessary consequences of the political targets for renewable energy expansions exceeding the consumption in Denmark.
	Creation of local jobs[1]	Concentrated in the construction phase – often in areas with modest economic activity.
	Highly productive and often relatively well-paid jobs	Affects income and purchasing power locally – especially in areas with modest economic activity.
	Increased activity in related industries	Derived activity in commerce, service and materials purchased from subsuppliers.
THE ENERGY SYSTEM	Facilitating a significant expansion of renewable energy	Production of green hydrogen constitutes relevant use and is necessary to follow through on the political ambitions for expansion of renewable energy – in particular in the North Sea.
	The hydrogen production enables the balancing of fluctuations in renewable energy in respect of the Danish power grid and the direct electrification	Reduces the need for renovation, expansion and reinforcement of the power grid and enables sector coupling.
	Hydrogen and PtX products as energy storage plants	No need for production and demand to match in terms of timeline.
	Reliability of supply	Own hydrogen production ensures a stable supply for Danish consumption in hard-to-abate industries and for PtX products.
	Excess heat from electrolysis may be used in the district heating network by near-by enterprises or offshore for desalting of sea water	Utilisation of excess heat depends on the hydrogen production location.
Commercial dynamics	Export revenue of up to DKK 100 billion (EUR 13.3 billion) annually when making full use of the potential.	Equivalent to one-tenth of the current exports of goods which will make green hydrogen one of the largest export industries, only surpassed by the exports of the life-science sector and the entire food cluster. Larger than the current exports of green energy and environmental technology.
	Valuable expertise	Innovation, knowledge and accumulation of experience for international use in connection with exports and projects.
	Stable and secure access to energy along the hydrogen network	Connections between the location of hydrogen infrastructure and the PtX enterprises and the geographical location of other hydrogen consuming enterprises.
	Changes in business structure affect derived industries	A large hydrogen market with an associated infrastructure affects the rate of establishment and localisation patterns for manufacturers, buyers and subsuppliers. The port functions change from support of primary industries (fishery) and extraction of resources (oil and gas) to support of establishment of offshore renewable energy and energy islands.

1 The establishment and operation of the hydrogen infrastructure will not lead to a permanent net boost in employment in case of an unchanged labour force as the people will seek employment in other parts of the economy in the absence of hydrogen production and establishment of a hydrogen infrastructure

***Box 9.1:** Climate impact of green hydrogen versus fossil-based hydrogen*

Fossil-based hydrogen (grey hydrogen) emits CO2e when consumed whereas there are no CO2e emissions from the production or use of green hydrogen.

According to the IEA (2021), the direct emissions from various forms of hydrogen are associated with the following climate intensity:

- Grey hydrogen: 10-14 kg CO2e/kg hydrogen
- Blue hydrogen (CCS 60%): 5-8 kg CO2e/kg hydrogen
- Green hydrogen: 0 kg CO2e/kg hydrogen

The Danish Energy Agency expects that 1 ton of green hydrogen replacing grey hydrogen will lead to direct displacement equivalent to 11 tons of CO2e.

The climate intensity does not include climate emissions linked to the production of the underlying means of production, production of hydrogen pipes etc. but the direct displacement only.

If, for instance, Denmark is able to produce 216 TWh2 of green hydrogen equivalent to 6.5 million tons of green hydrogen and replace similar quantities of grey hydrogen in, say, Germany, the climate will be spared annual emissions in excess of **70 million tons of CO2e**. This corresponds to nearly **one-tenth of Germany's total CO2e emissions** in 2022 of 761 million tons of CO2e. If instead the green hydrogen replaces the use of oil or coal, for instance via green PtX fuels, the climate impact will increase further.

In other words, as a producer of green hydrogen Denmark will be able to **displace 1.5 times Denmark's own emissions** on Danish soil which constituted approximately 44 million tons of CO2e in 2021, according to Statistics Denmark.

In terms of the potential green hydrogen production and the distribution of expected exports and domestic consumption, respectively, exports of approximately 198 TWh are to be expected. This could supply a little less than 6 million tons of green hydrogen annually and lead to displacement of 65 million tons of CO2e, if it replaces grey hydrogen or about 8.5% of Germany's total emissions.

In the long term, direct consumption of 19 TWh or a little more than 0.5 ton of green hydrogen is expected in Denmark. Assuming that this replaces fossil fuels with the same negative impact on the climate as grey hydrogen, **Denmark's annual climate emissions will be reduced by 6 million tons of CO2e**. In comparison, a green tax reform with a carbon tax imposed on the business community (the manufacturing industry) is expected to contribute an annual climate impact reduction of 4.3 million tons of CO2e leading up to 2030. The green tax reform consists partly of taxes and partly of grants. A call for tender initially suggests another measure, namely CO2 capture, and that Ørsted expects to capture 0.4 million ton of CO2e annually from 2025 in the form of CCS at the Asnæs and Avedøre combined heat and power plants, to which the CCUS Foundation has supplied funding of EUR 1.1 billion. Therefore, green Danish hydrogen could play a significant role in a national context as well as in terms of Denmark's own climate targets.

Source: IEA (2023), Agora Energiwende, the Danish Ministry of Climate, Energy and Utilities (2023) and own calculations

2 This is equivalent to Denmark's potential production of hydrogen, see the CIP Foundation's Market Assessment, March 2023, and the quantities included in the proposal for a future hydrogen infrastructure

Box 9.2: *Does green hydrogen and exports cause spill-over effects which reduce the climate impact?*

Kraka Advisory (2023), among others, has advocated that production of green hydrogen in Denmark and the subsequent exports may cause spill-over effects which reduce the climate impact, partly through the EU quota system for CO2e emissions, partly by using power that could otherwise have been used for the direct electrification or which is not green.

Spill-over through the EU quota system with lower demand for fossil fuels leading to lower quota prices and an increased consumption?
It is argued that increased production of renewable energy, green hydrogen or PtX products which displace fossil-based energy also lower the price of the CO2e quotas in the EU Emissions Trading System (ETS) when the demand for fossil-based energy decreases. If the quota prices go down, the demand for fossil-based energy increases temporarily (spill-over). However, this will be the case whether fossil-based energy is being displaced by one green energy source or the other and is therefore not specifically linked to hydrogen or PtX products; it is more likely the result of a political resolve to displace fossil-based energy for the benefit of the climate. This is also applicable when other measures are taken, for instance entrainment requirements for fuels which lead to a drop in fossil-based fuels and, in consequence, the quota prices. Spill-over requires a significant drop in the CO2e quota prices to make the fossil alternative, including the quota price, cheaper than the green alternative.

However, the potential spill-over effect is limited by the fact that the CO2e quota price increases over time and that the EU ETS system also reduces the quantity of accessible quotas over time. Add to this the commercial pressure associated with the enterprises' climate reporting which may impede an increasing fossil-based energy consumption.

As the political targets for decarbonisation draw closer and the sector requirements are enforced, it is increasingly less likely that the fossil-based energy consumption will rebound. If increasing CO2 quota prices are not enough to instigate the change, it may be necessary to ban fossil-based energy if the political targets for climate neutrality are to be achieved.

Spill-over, if the quantity of green power does not suffice?
Another possible spill-over effect scenario is if the hydrogen and/or PtX products are either based on non-green power sources or based on green power that could otherwise have covered the direct electrification need. In this case, the EU has also proposed relevant regulation measures as green hydrogen has to be based on green power in order to be certified as green hydrogen. Moreover, it has to be additional renewable energy in order to not displace the green power for direct electrification. See Chapter 2 for further elaboration.

9.3. Our greatest green export opportunity

In 2022, Danish exports of energy technology amounted to a little more than EUR 8.4 billion or 6% of Danish exports of goods, of which 61% relates to wind energy[3]. When adding exports of green environmental technology, the value of Denmark's current green exports of goods (wind turbines, water technology, energy efficiency etc.) was approximately EUR 11.6 billion in 2022, according to the Danish Ministry of Climate, Energy and Utilities (2023), or 9% of total exports of goods.

EXPORT REVENUE UP TO EUR 13.5 BILLION
In comparison, the future exports of green hydrogen are expected to total approximately EUR 1 billion by 2030 and increase to approximately EUR 13.5 billion annually once fully phased in (fixed prices). This corresponds to approximately one-tenth of Danish exports of goods in 2022. Consequently, new green exports seem to be able to reach Denmark's current export level which is the result of development and extensive work over a number of years. An export opportunity of this size is a rarity.

Overall, an expansion of the green hydrogen production and the associated exports will create a permanent source of revenue for Denmark which additionally exceeds the previous revenue from for instance oil and gas exports which peaked in 2012 with a net export value of approximately EUR 8.3 billion in 2012 prices, according to Statistics Denmark.

Net oil and gas exports are based on the extraction of a limited natural resource which will be depleted over time whereas green hydrogen is based on a renewable source.

The combined public sector revenue from the extraction of hydrocarbon in the North Sea[4] since the onset in 1972 and until 2020 total approximately EUR 72.5 billion for this period (in 2020 prices) and peaked in 2008, according to the Danish Energy Agency[5].

Over time and as the market for green hydrogen expands, the public sector revenue generated from this source of energy will help finance the welfare state and constitute a more permanent source of income.

At the same time, the green hydrogen market may contribute to an increase in exports of green power. The significant expansion of renewable energy for servicing of the hydrogen production will periodically enable a certain balancing of the Danish power grid and, as a result, derived energy exports. The synergies between the production of electricity and hydrogen will enable larger production as compared to a scenario where the expansion only applied to renewable energy for the electricity market.

IS GREEN HYDROGEN ABLE TO DELIVER ON THE POLITICAL TARGETS FOR RENEWABLE ENERGY?
According to the Climate Act, Denmark is not only required to focus on the national targets for CO2e reductions but also to act as a pioneer country and an example to follow[6]. This becomes the case once the Danish hydrogen production not only covers the domestic need for supply but is also able to supply Denmark's closest neighbouring countries with some of cheapest green hydrogen produced in Northern Europe.

3 The Danish Ministry of Climate, Energy and Utilities (2023)
4 By means of corporate taxes, hydrocarbon taxation and payment of dividend in the Nordsøfonden, which is responsible for the Government's participation in extraction of oil and gas with a 20% share of ownership.
5 Economic aspects of oil and gas production | The Danish Energy Agency (ens.dk)
6 "Derfor skal Danmark være et foregangsland i den internationale klimaindsats, som kan inspirere og påvirke resten af verden" (The reasons why Denmark must act as a pioneer country in the international climate effort in order to inspire and influence the rest of the world), the Danish Ministry of Climate, Energy and Utilities, 2019.

In terms of climate considerations, Denmark is a pioneer country when the country:

- facilitates climate reductions in other countries in the most cost-effective way
- supports direct climate reductions equivalent to one-tenth of Germany's current emissions or 1.5 times Denmark's current climate emissions
- targets net zero in 2045

An expansion of renewable energy to support hydrogen production is also necessary in order to provide renewable energy on the scale which is presupposed by various political declarations regarding the North Sea and the Baltic Sea, respectively. This vastly exceeds the quantities which the power grids of the various countries are able to receive directly, and the quantities needed for direct electrification; therefore, part of the expansion of renewable energy decided at Government level must be adaptable to other forms of energy, which can be stored and adjusted to the level of consumption. Green hydrogen is able to achieve this.

9.4. Other beneficial effects on society

IMPACT ON EMPLOYMENT AND ACTIVITY LEVEL LOCALLY AND BEYOND THE LARGEST CITIES

Hydrogen production and the establishment of the hydrogen infrastructure will – as it appears from the CIP Foundation's development proposal – especially take place in areas of Denmark outside the major cities which are not already characterised by a high level of economic activity.

It will typically involve skilled labour or people with university degrees for the establishment and operation of the hydrogen infrastructure and production and thus relatively well-paid and productive jobs in the private sector. Add to this jobs and economic activity, typically in local trade and services as well as with subsuppliers.

The local employment effects will typically be of a temporary nature and follow the extension phases, also geographically to a certain extent. No estimates have been made of the possible employment effects of the CIP Foundation's total development plan as it requires detailed knowledge of the plans of the individual stages etc.

Each stage is subject to considerable uncertainty as the development plan extends over a period of 25 years with some overlapping stages which are already on the drawing board with the public sector infrastructure enterprises.

By comparison, COWI (2021) has calculated the possible employment effects of the construction of the Fehmarnbelt Link which is the largest infrastructure project in Danish history so far, and the conclusion is that the construction phase will involve approximately 20,000 full-time equivalents in direct effects supplemented by 22,000 full-time equivalents of indirect effects during the period 2020-2029. The estimated capital investment in the Fehmarn Belt was originally estimated at EUR 7.3 billion (in 2015 prices). Since then, the project has turned out to be considerably more costly, for instance as a result of the expansion of German railway facilities.

VALUABLE EXPERTISE

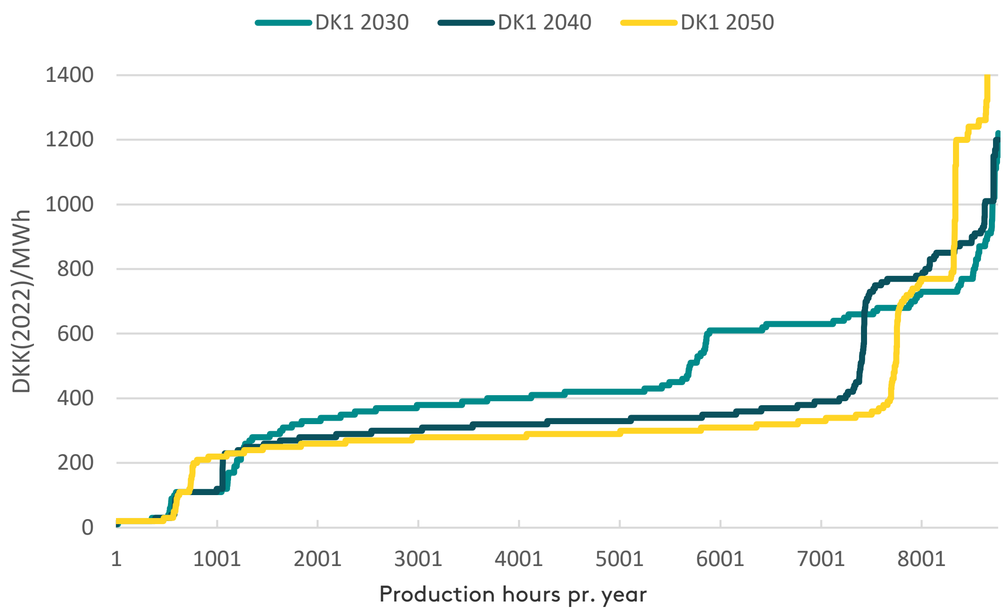
The enterprises involved in the construction of the hydrogen infrastructure, or the hydrogen production will – in addition to commercial investments – accumulate knowledge and expertise in the areas of construction, installation and application of technology as a consequence of being pioneers, and this is highly valuable for future projects. This applies whether they are carried out in Denmark or abroad.

This kind of learning effects pave the way for special insights from the very beginning but are also costly in the form of investments in innovation and tests in order to identify the best solutions. However, the resulting competitive edge will make up for this over time.

As an example, Denmark has been a pioneer country when it comes to the production of wind turbines and the utilisation of the wind resources onshore as well as offshore. And this has been beneficial for the Danish enterprises participating in this process in terms of considerable knowledge and know-how which can be exported as solutions to the entire world.

When the US provides substantial grants for hydrogen and PtX production over a 10-year period via the Inflation Reduction Act, it is an investment intended to attract developers and thus ensure American business life exclusive access to new technologies and new methods during a time of limited resources. All things considered, this will limit the development activity and accumulation of expertise in other parts of the world, includ-

Figure 9.1: *Distribution of hourly electricity prices over time (duration curve)*



Source: The Danish Energy Agency (2022) ing Europe, during this period. The response from the EU and the Danish follow-up should be seen in the light of this.

LOWER PRICES OF GREEN POWER

In case of substantial expansion of the renewable energy network which will also include balancing of the electricity system, electricity prices will be lower for more hours a year and consequently entail a fall in average electricity prices, especially for consumers with a certain consumption flexibility.

Figure 9.1 shows the development in electricity prices per hour, once more renewable energy enters the grid (duration curve). Whereas the development of prices was relatively stable in 2020 without any major difference between the cheapest hours and the most expensive hours (peak hours), the future price curves based on more renewable energy will lead to more hours with either higher or lower prices compared to today and therefore greater fluctuations in electricity prices.

The figure shows that for long periods of the year in the time to come, prices will fall below the previous normal level (in an expanded wind scenario). For buyers of electricity with the option of flexible consumption it will be an advantage as they can choose to time their consumption within these periods. This applies to for instance hydrogen and PtX manufacturers, but also other enterprises and private consumers. On the other hand, buyers of electricity in need of stable supplies will experience hours at much higher prices than previously (peak hours).

When the average electricity prices go down, it is not only beneficial for the enterprises producing PtX products from green power; on the contrary, it is an advantage to all power-consuming enterprises and consumers with the option of exhibiting a certain degree of flexibility in their consumption. In this case, the costs decrease. Once the transition is of a structural nature, the result will be permanently lower electricity prices on average.

When the lower electricity prices become a reality, it will to some extent serve as a reminder of what happens if electricity prices are reduced by means of reduced taxes resulting in increased economic growth, activity and a more productive workforce[7].

Low income groups will, relatively speaking, benefit the most from lower electricity prices on average as the electricity consumption constitutes a larger share of the disposable income of this group.

DENMARK AS A GREEN PIONEER COUNTRY

Although the establishment of infrastructure for a new market in its infancy involves risks as described in Chapter 8, the process also brings about benefits – temporarily and permanently – for Denmark which may help achieve the political ambitions for the green transition, create new sources of revenue and drastically change the business structure and the energy policy in the next decades and make Denmark a green pioneer country once again.

7 See also Højbjerre, Brauer and Schultz (2017).

Benefits of expanding the hydrogen infrastructure

Supports the green transition of a major region when Denmark is able to produce large quantities of green hydrogen for Northern Europe in the most cost-effective manner for the necessary transition in the industrial and transport sectors and displace CO2e corresponding to one-tenth of total German emissions or 1.5 times the current emissions in Denmark.

Revenue from the export of renewable energy of up to EUR 13.5 billion annually – in line with the export of green energy and environmental technology – and with resulting tax revenue for the welfare state.

A more independent energy supply for the benefit of European energy and security politics.

Balancing of the power grid, when hydrogen is produced, when it is really windy, when the sun is shining and a less imperative need to expand the power infrastructure for the transmission of the large quantities of renewable energy which are required for the direct electrification process.

Lower energy prices to the benefit of Danish households as well as corporate competitiveness.

Local workplaces with a high level of productivity and relatively high wages. During the construction phase and the subsequent operation with a geographical variation, mostly outside the major cities and a spill-over effect on related industries.

Companies choose locations with a secure and stable energy supply. With a well-expanded hydrogen infrastructure, it is possible to attract and retain companies with energy-intensive processes which need a secure and stable supply of green hydrogen or production of PtX products.

Development of new industries and expertise which entails first mover advantages that can be utilised for subsequent projects at other locations.

Source: Own analyses based on input from COWI, Copenhagen Economics (2022) etc., 'De samfundsøkonomiske gevinster ved rettidige investeringer i dansk energiinfrastruktur' (The economic benefits of timely investments in Danish energy infrastructure), September 2022.

A roadmap for the expansion plan

Chapter 10

In order to realise the outlined expansion plan, a number of decisions have to be made at central level within a short time span; for example, out of consideration to the developers and contractors who are to build the infrastructure. If, for instance, an onshore hydrogen backbone infrastructure is to be ready for operation in 2028, orders for the required pipes and components must be placed in the coming year. Consequently, the fundamental decisions which will shape the framework for the hydrogen infrastructure of the future and the conditions for the commercial progress must be made already in 2023.

At the general level, it is imperative that decisions are reached concerning the public calls for tenders for the offshore wind and the open-door projects to ensure sufficient renewable energy both for the electrification process and for the hydrogen production.

CONNECTION CONTRACTS WITH OTHER COUNTRIES

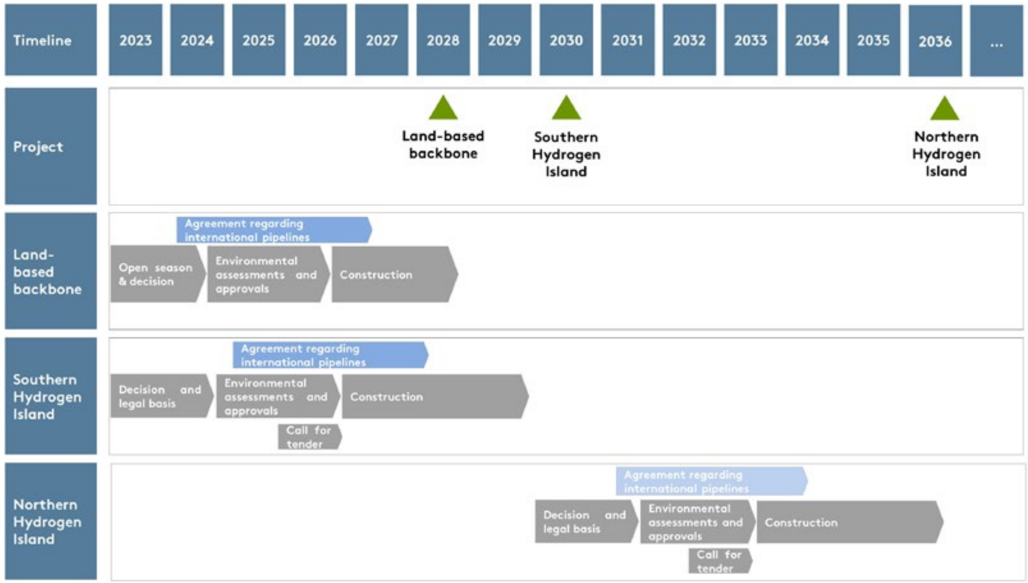
In order to facilitate a Danish hydrogen infrastructure and with this large-scale hydrogen production in Denmark, it is absolutely critical that the Danish planning authorities engage in a binding dialogue with relevant international players in parallel with the decisions to be made at national level. Since much of the Danish hydrogen will be exported to other countries, the conclusion of connection contracts is essential in order to ensure that a Danish hydrogen infrastructure can be connected to an international hydrogen infrastructure and that the dimensions of this infrastructure are of a scale that will allow transmission of the quantities Denmark will be producing.

Denmark's involvement in this dialogue should not only be about connections and conditions. Contracts concerning international interconnections must be concluded before the large hydrogen projects reach the kick-off phase since these contracts will define the conditions for the sale of hydrogen and market access.

As an example, 48" hydrogen pipes will be required for the proposed expansion project in order to manage the future quantities. This will have to be coordinated with the buyers/consumers to ensure agreement between the quantities produced and transmitted within Danish territory and what can be received, especially in Germany. The timing must also be right to ensure that the pipelines are ready for operation on both sides of the border at practically the same time.

The decisions to be made at the heart of this issue are discussed below in relation to the expected process involved in establishing the hydrogen infrastructure projects.

Figure 10.1: *Decisions required for the development of a Danish hydrogen infrastructure designed for large-scale production*



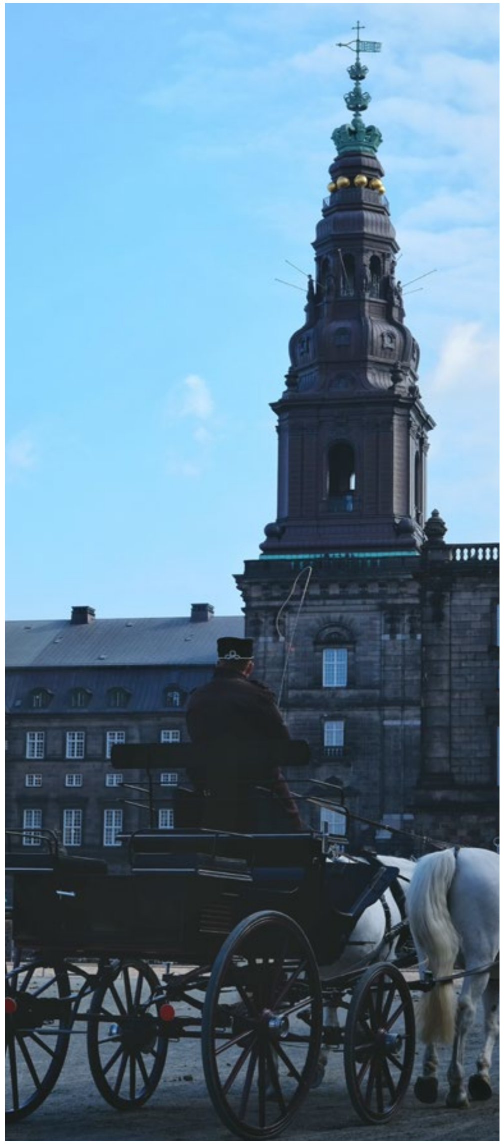
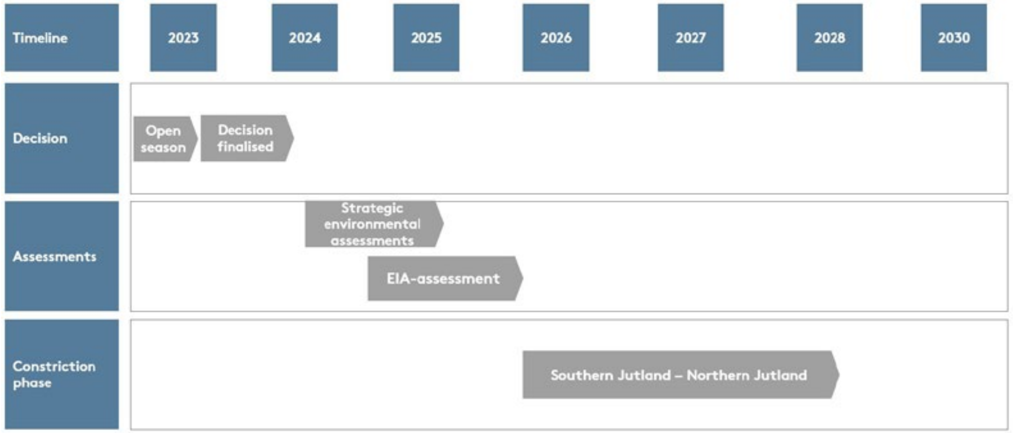


Figure 10.2: *Illustration of time schedule for the construction of an onshore backbone*



10.1. Deciding an onshore backbone

The agreement between Denmark and Germany for the construction of an onshore hydrogen interconnection between Northern Germany and Western Denmark is in fact a Letter of Intent where the two countries agree to join forces to roll out a market-driven hydrogen infrastructure and to integrate the energy systems of the two countries. As such no concrete political decisions have been made nor any decisions concerning facilities.

For Denmark, the decision to establish the required facilities is in the hands of the Danish TSO, Energinet (and is subject to approval by the Ministry of Climate, Energy and Utilities), whereas the question of funding remains unresolved.

Consequently, to realise the construction of an onshore backbone in Jutland the politicians have to reach a decision in 2023 concerning the funding of a Danish onshore hydrogen infrastructure from Northern Germany to Northern Jutland. This is a condition for providing the players involved with the security they need and for the backbone to be operational by 2028.

The Danish TSO, Energinet, should instigate an open-season process to resolve the questions about the scope and dimensions of the infrastructure in a dialogue with market players and German planning authorities before the expansion plan is given political approval in 2023 prior to the environmental surveys. By experience, the actual construction phase needs not be long, and as regards the question of duration, the construction of the Baltic Pipe can serve as an example of an infrastructure project of similar scope. For this project, the design and planning phase lasted about 12 months, according to COWI, and the construction as such lasted about 24 months.

The coordination between Energinet and Evida (Danish gas distributor) is a focal point in order to ensure optimum timing of the construction process and timely connection since it is essential that there is agreement between the time when the transmission part is operational and when the producers (and buyers/consumers) can be connected to the interconnection.

DECISIONS ON CONDITIONS FOR CONNECTION, TRANSMISSION AND STORAGE

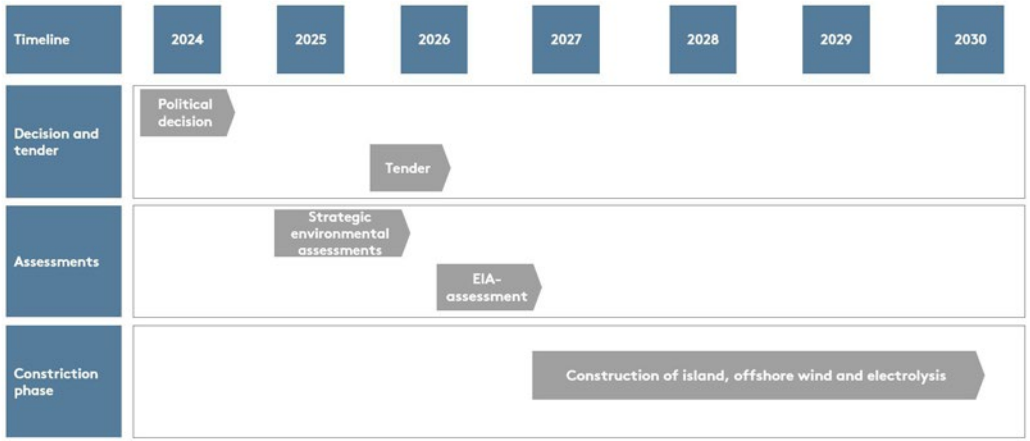
As already mentioned, along with a physical infrastructure also clearly defined, long-term framework conditions for connection and usage must be available. Consequently, the terms and conditions for use of the onshore hydrogen infrastructure by producers and buyers/consumer have to be decided in 2023. More specifically, the fundamental principles have to be laid down so that the long-term framework conditions can be announced, allowing decisions to be made regarding the investments in hydrogen producing facilities and renewable energy.

10.2. In-principle decision concerning the development of the North Sea

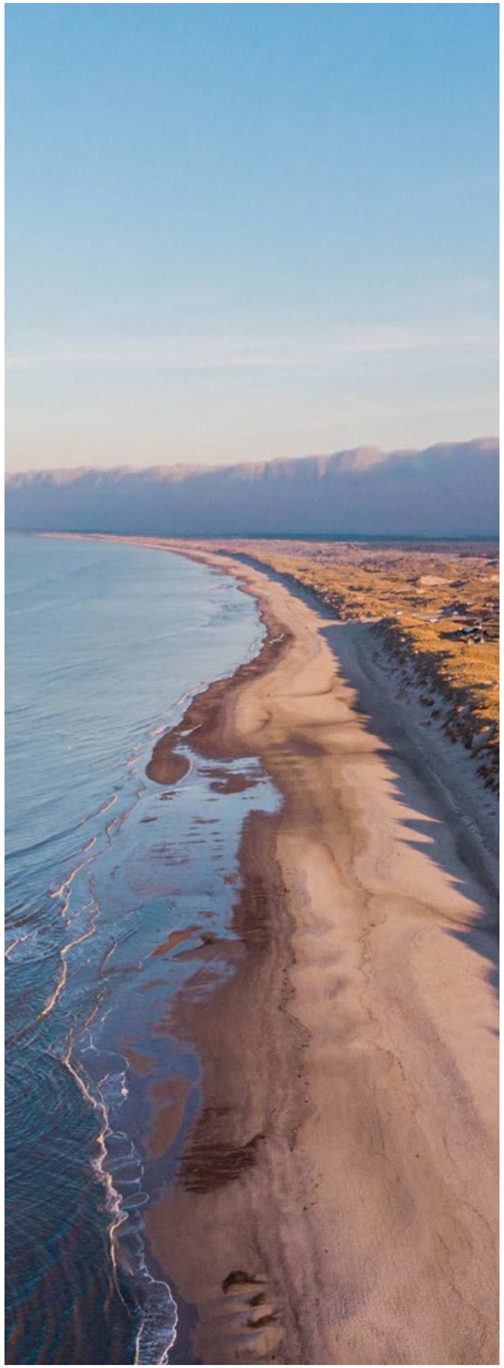
An early in-principle decision is required at the political level – preferably already in 2023 – regarding the use of Denmark's North Sea areas – a revised offshore plan. Which areas can be used for the production of renewable energy and hydrogen and on what terms and conditions?

At the heart of this lies the need to include the areas in the Danish part of Dogger Bank since producing renewable energy is very attractive and the areas are in close proximity to Denmark's most important export markets. Furthermore, the in-principle decision should come with a clearly defined framework for the development of hydrogen production in the North Sea, which will lower the risk and

Figure 10.3: *Visualisation of the time schedule for the construction of the Southern Energy Island*



1 Ingeniøren (2022)



make the entire project more transparent to investors and developers. The objective is to speed up the offshore expansion process and make the best use of the North Sea areas.

10.3. Deciding a southern hydrogen island at Dogger Bank

In view of the in-principle decisions concerning the expansion of the production in the North Sea to include hydrogen production, the planning legislation etc., calls for tenders for a southern hydrogen island should be initiated. Considering that both preliminary investigations and construction take time, the process should be initiated as early as 2024. If the legal basis is in place by 2024, the Danish players can commit themselves when negotiating the connection procedures and the dimensions of the international interconnections with the international players.

Once the legal basis and the international interconnections are in place, the EIA review process and the call for tenders can be initiated. Some issues might arise for infrastructure projects of this nature if the soil conditions are found to present potential risks, as was the case with the state-owned energy island in the North Sea1 where a sediment valley was identified in 2022. Such findings can both add to the costs and cause delays, and since the EIA procedure cannot be initiated until a strategic environmental assessment has been performed, it is recommended to take the required initiatives with the intention to conduct the studies in parallel.

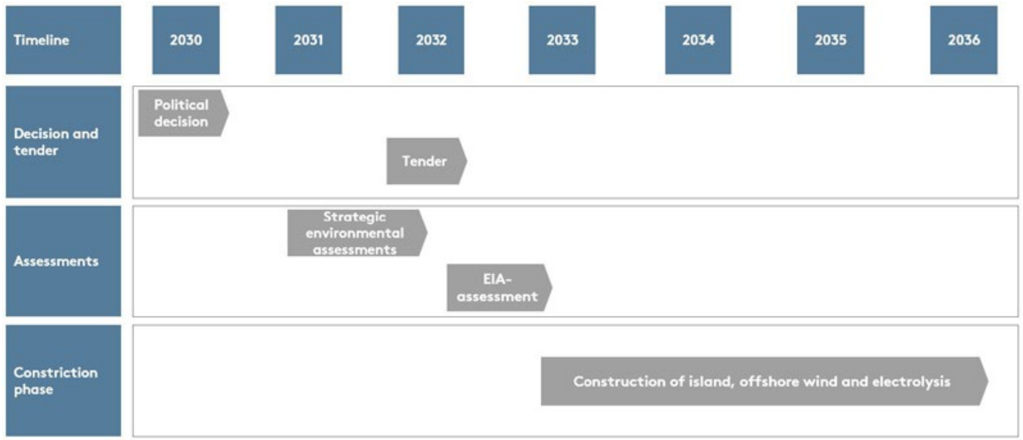
This could pave the way for speedier clarification of the offshore potential to the benefit of developers, investors and the general pace of the construction and expansion of renewable energy projects. The tendering process for the energy islands comprises separate calls for tenders for the construction of the island and the offshore wind farms. The islands will also comprise an innovation zone which the successful tenderer can use for hydrogen production, for example. Since the Southern and Northern Hydrogen Islands are both assumed to be dedicated hydrogen islands (as the primary production with an option to also export electricity), it is recommended that the calls for tenders include the islands and the dedicated wind farm as a whole and to be built in parallel. This would shorten the time spent on the tendering process while ensuring the best possible use of the areas.

10.4. Deciding a northern hydrogen island

In view of a political in-principle decision and considering the lessons learnt from the state-owned energy island and a southern hydrogen island, the tendering process for the Northern Hydrogen Island has to commence in 2030 at the latest. Both the preliminary investigations and the construction work will be extensive, as will be the case with the Southern Hydrogen Island. The process from the adoption of the legal framework to operation is expected to be the same as for the Southern Hydrogen Island although some optimisation of the process could be assumed. Ideally, the international interconnection from the Northern Hydrogen Island is already in place when the Southern Hydrogen Island is to be built, see Chapter 6.3.

Once made, the above decisions will create the framework for a coherent hydrogen infrastructure in Denmark by 2045. This infrastructure will have the capacity to hold the quantities in high demand by the market and will be built on the political ambitions to expand the production of renewable energy.

Figure 10.4: *Visualisation of the time schedule for the construction of the Northern Energy Island*



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