Recommendations for a Danish Power-to-X strategy

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DANSK ENERGI

Foreword

Power-to-X (PtX) is a crucial solution that can replace our last fossil fuel consumption in industry, heavy-duty vehicles, shipping and aviation. PtX will thus be a major contributor to solving the global climate challenges. We generally understand the technology and know what it will take to put it to work. Firstly, the price must be reduced, so the green alternative becomes competitive with the fossil fuel products used today.

The learning curve will be steep, and development must be faster than ever if we are to succeed in the coming decade. We believe Denmark can and must play a key role in this development.

With the skills and resources available to us, we can make green energy the core of Denmark's future growth and prosperity, and make Danish companies more competitive. The existing green resources from renewable energy provide the foundation, but it is not enough to focus solely on how we can produce PtX products cheaply and effectively. The goal is not just to produce green energy, but increasingly, to displace fossil energy. If the transition is to succeed, we must focus just as much on the sustainable transformation of the Danish companies that will use the PtX products, as on ensuring that these maintain and, if possible, improve their competitiveness.

Danish Energy has therefore taken the initiative to bring together key companies across the entire value chain, in order to make specific recommendations for how to design a Danish PtX strategy that will contribute to solving the planet's climate challenges, ensure the competitiveness of Danish companies and make Denmark wealthier.

Lars Aagaard CEO, Danish Energy
Jesper Hjulmand CEO, Andel
Lars-Peter Søbye CEO, COWI
Kim Fausing CEO, Danfoss
Lars Sandahl Sørensen CEO, DI
Jens Bjørn Andersen CEO, DSV Panalpina
Thomas Egebo CEO, Energinet
Roeland Baan CEO, Haldor Topsøe
Claus Madsen CEO, ABB Power Grids Denmark A/S, Hitachi ABB
Thomas Woldbye CEO, Copenhagen Airport
Søren Skou CEO, Maersk
Niels Duedahl CEO, Norlys
Simon Pauck Hansen Executive Vice President, SAS Danmark
Finn Bjørn Schousboe Business Manager, Dansk Shell
Peter Weinreich-Jensen CEO, Siemens Energy
Jacob Nørgaard Andersen Country Manager, Vattenfall Danmark
Torben Skyum-Jensen CEO, Yara Danmark A/S
Henrik Poulsen CEO, Ørsted

Figure 1.
The four key components

Ambition

- An ambitious PtX programme to ensure that Denmark's major strengths in relation to PtX are exploited, to help make Denmark fossil-free and contribute to the global green transformation through the export of energy and technology
- This ambition has to support a reduction of 2.5 million tonnes in carbon emissions in Denmark by 2030

National action

- Kick-start the Danish PtX efforts through subsidies and regulation
- Establish the structural basis for full industrialisation of PtX products. Focus on the production of PtX products with a view to reduce costs
- Maturation of the buyer side and increase demand for PtX products

International action

- Implementation of rules and frameworks for an international market where the value of renewable hydrogen is clear
- Boost international demand for PtX to avoid a decline in the competitiveness of Danish companies and to create a market for Danish PtX products and technologies

Dynamic governance

- PtX requires a completely different and agile form of collaboration between industry and government compared to what has been common practice in Denmark
- Danish companies have their feet held to the fire, but also have their finger on the pulse, as they are the ones who have to invest in both production and consumption
- Establish a clear governance structure where the business sector is continuously involved and consulted about future adjustments to the PtX strategy, and where the government provides ongoing reporting on implementation of the strategy

Summary

Recommendations for solving the PtX paradox – an agile and ambitious Danish PtX strategy

The climate is not just a national, but also an international concern. Denmark has taken responsibility. We are leading the way, having set an ambitious reduction target of 70%, and committed ourselves in the Climate Act to making a contribution to solving global challenges through the export of green energy, technology and solutions.

There is broad consensus internationally among experts, the business sector and politicians that PtX will be needed to achieve the Danish and European goal of full climate neutrality by 2050. Several Danish climate partnerships and the government's climate programme also indicate that PtX products will have to be in use before 2030 in order to achieve the 70% reduction target.

Preparations for PtX production and applications are already in full swing in several European countries, such as Germany and the Netherlands, and the EU has a clear target of establishing 40 GW of electrolysis by 2030. Countries have begun positioning themselves for the future PtX market, and Denmark is not at the forefront. But we could be.

Power-to-X has great climate and economic potential
In Denmark, PtX is particularly relevant for decarbonising heavy transport (heavy-duty vehicles, aviation and shipping), and this will be essential in order to achieve the 70% reduction target.

Denmark is well placed to assume a strong industrial position in the field of PtX, with its strong energy system and competitive green electricity production, its great potential for sector coupling and a good geographical location for exporting PtX products and technologies.

However, PtX products are currently far from competitive with fossil fuels, and consumer willingness to pay cannot cover the higher prices for green products and services. Effort must therefore be made to bring down the costs of PtX. Much can be achieved through lower electricity prices as a result of the expansion of renewable energy, but support will also be needed for the industrialisation of PtX production and industry.

It is currently uncertain which green fuels will end up being most competitive, where they will be used and how quickly this will happen. PtX production can either be centralised , where green electricity is produced using large offshore wind turbines, onshore wind turbines or solar cells, or decentralised, close to where the PtX products are used. These various outcomes impose different requirements for the location of production and consumption and for the development of infrastructure, demanding coordination, agility and room to manoeuvre.

Denmark faces a Power-to-X paradox, and must consider its own competitiveness
Denmark is facing the fundamental, structural paradox that we currently have neither significant production nor consumption of PtX products, and there is not yet a cohesive European market with the necessary infrastructure.

Looking at the demand side, consumers will only buy and use PtX products and make the technology choices necessary for the transition when the price of the products is competitive. Yet the products will only become competitive when production has been scaled up, which will only commence when there is certainty of buyers – i.e when consumers demand or commit themselves to buying the products. We call this the PtX paradox.

Denmark has a small, open economy with foreign competition, and measures must be chosen carefully to ensure that Danish companies are not disadvantaged compared to foreign ones. It is therefore necessary to consider Danish competitiveness when determining national initiatives, and efforts should be made in parallel to establish European and international initiatives.

The pieces of a Danish PtX industry must be put together now

The Danish Folketing has to pave the way for the future PtX industry in Denmark within the next six months. This means that the government and a majority in the Folketing have to adopt an ambitious and agile strategy covering the entire value chain, from production to the use of PtX products. The government must set aside around DKK 10 billion between 2021 and 2030 to kick-start and industrialise PtX production, and support technology change in sectors that will be using PtX products.

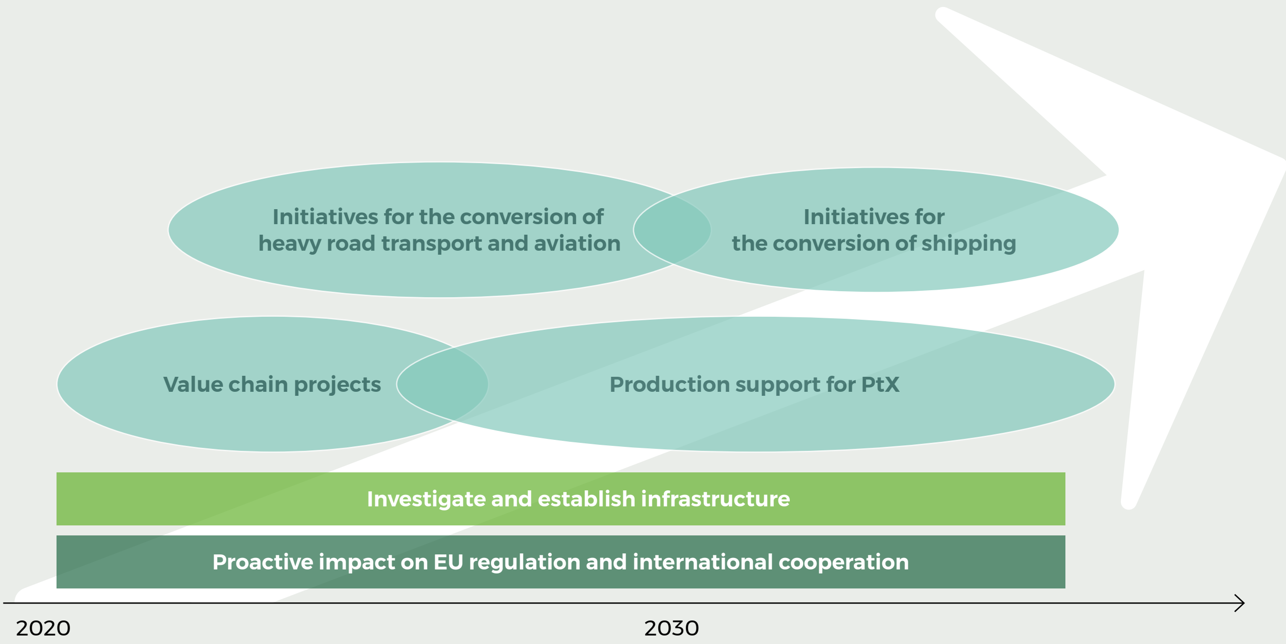
Political involvement and a willingness to invest are essential in order to exploit the great commercial potential of PtX in Denmark. Some of the framework conditions are politically determined, and the risks associated with the development and consumption of PtX products are too great for commercial operators to take on alone. Without political involvement, progress will be too slow for us to achieve the final difficult step towards the 70% carbon reduction target by 2030. This would leave Denmark behind while other European countries position themselves as leaders in PtX.

We need to solve the PtX paradox, in order to kick-start both the production and use of PtX products. We have therefore identified a strategy with four key components:

- An ambitious effort that supports a reduction of 2.5 million tonnes in carbon emissions by 2030
- A national effort to kick-start production and usage, e.g. through subsidies
- An international effort to establish rules and market frameworks, and to create greater demand for PtX products and technology
- Strong governance, where the business sector is continuously involved and consulted regarding future adjustments to the PtX strategy

The recommendations in this report are a complete proposal for how to solve the PtX paradox, and kick-start PtX production and usage in Denmark. It is a comprehensive solution that demands focus on and investments in the entire value chain. The recommendations provide a roadmap for how to get started and how to ensure further industrialisation. This roadmap contains various phases, starting with value chain projects, initiatives for the conversion of heavy road transport and aviation, the establishment of infrastructure and impact on EU regulation and international organisations. This is followed by production support for large-scale PtX production, measures for the conversion of shipping, further development of infrastructure and continued impact on EU regulation.

Figure 2.
Conceptual roadmap



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1. Introduction to Power-to-X

Power-to-X (PtX) is defined in this context as the process of converting green electricity into hydrogen or PtX products based on hydrogen. The first part of the PtX process is to use green electricity to power electrolysis plants where hydrogen is split from water. The hydrogen can then either be used directly as a fuel or as an element in making hydrogen-based fuels in a synthesis plant. PtX products are produced by adding either nitrogen or carbon (see Figure 3).

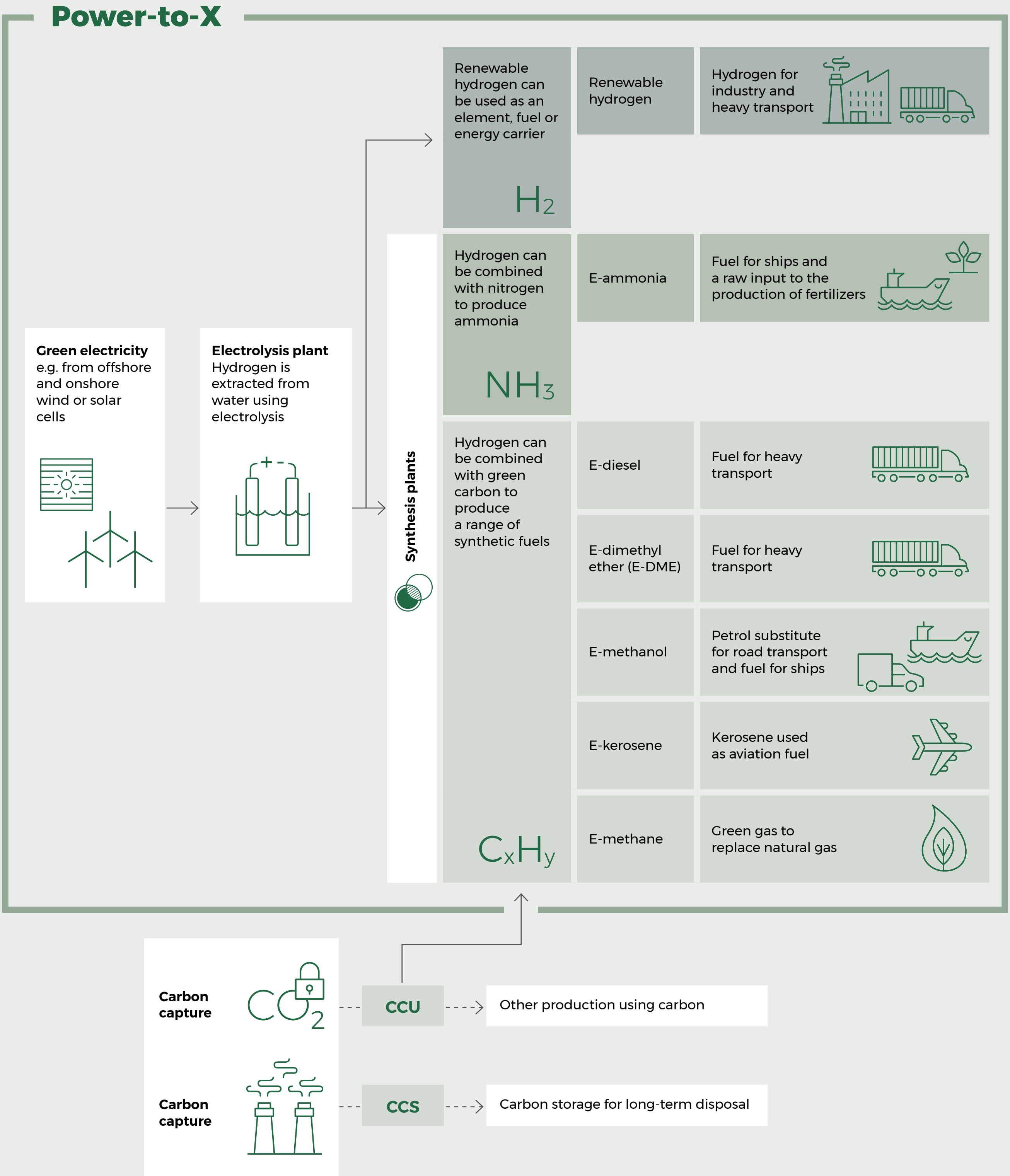
When producing PtX products using carbon, it is important that the carbon is green. Green carbon can be obtained via carbon capture at large green, biogenic sources, e.g. from biogas and biomass plants, and then used for the production of PtX products (carbon capture and utilisation, CCU). Instead of using the captured carbon, you can store it (carbon capture and storage, CCS) – an alternative way to reduce carbon emissions. CCS is ideally suited to large fossil fuel point sources, where green alternatives are difficult to find, such as in cement production, but CCS can also be used to deliver negative carbon emissions by storing carbon from biogenic sources. Direct Air Capture is also being researched and industrialised, where CO_2 is captured from the air rather than a concentrated carbon source.

Possible applications for PtX products
Renewable hydrogen can be used as an element in certain industrial processes, as a fuel in industry and as an efficient energy carrier[1] in heavy road transport (see Figure 3). As an element, hydrogen is primarily used in the chemical industry, e.g. in alloys and paints. As a fuel, hydrogen is particularly used in high-temperature processes in the petrochemicals industry, such as refining crude oil for diesel or petrol. As an energy carrier in heavy transport, hydrogen is converted into electricity in a fuel cell, which drives an electric motor in a truck, bus, train or ship. In this context, it is an advantage that hydrogen can be stored.

By adding nitrogen to hydrogen in a synthesis process, green ammonia (e-ammonia) can be produced. This can either be used for fertilizer, or eventually as a fuel in shipping. The production of ammonia for fertilizer is currently the largest consumer of fossil hydrogen worldwide, and PtX can play a major role in decarbonising the agricultural industry. Ammonia can be produced in unlimited quantities, as nitrogen is not a limited resource.

By adding carbon to hydrogen in a synthesis process, e-diesel, e-methanol, e-kerosene, e-dimethyl ether (E-DME) and e-methane can be produced. These fuels can directly replace current fossil fuels, and can therefore be readily used in road transport, shipping and aviation.

Figure 3.
Power-to-X from production to application



SOURCE: Danish Energy, Bain & Company analysis.

Cost components in the production of PtX products
Estimated production costs for renewable hydrogen today consist mainly of electricity costs (51%) and the associated electricity tariff[1] (20%) (see Figure 4).

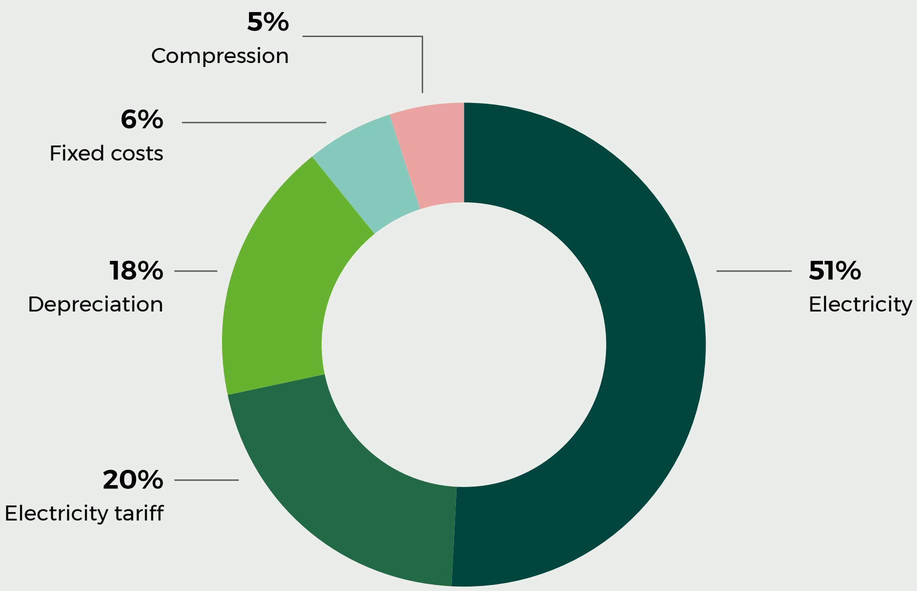
Another significant cost component is the depreciation of investments (18%). Most of this is linked to the electrolysis plant[2].

Compression of the hydrogen is another cost item (5%). This is done to keep storage and transport costs down. Fixed costs are estimated at 6% of the total production cost for renewable hydrogen.

For PtX products involving nitrogen or carbon, the cost of renewable hydrogen will account for 60-75% of the cost of production, depending on the energy density required in the products. The cost of green carbon will be around 10-15% for the PtX products requiring carbon.

[1] The electricity tariff depends on where in the grid the plant is connected. Even though the plant is connected to the distribution network, the electricity tariff consists primarily of the transmission tariff.
[2] Other investments include buildings, transformers, frequency converters, etc.

Figure 4.
Production cost elements for renewable hydrogen in 2020 (%)



NOTE: The electricity tariff is a transmission and distribution tariff.
SOURCE: Ea Energianalyse, Danish Energy, Bain & Company analysis.

Figure 5.
Various forms of hydrogen
Hydrogen can be produced in several ways, with different carbon emissions and effects on the climate.

	Fossil hydrogen	Low-carbon hydrogen	Renewable hydrogen
Names in the EU hydrogen strategy	Fossil-based hydrogen	Fossil-based hydrogen with carbon capture Low-carbon hydrogen	Renewable hydrogen Clean hydrogen
Definition	Hydrogen produced using fossil fuels, primarily from natural gas via steam methane reforming (SMR)	Hydrogen produced using fossil fuels combined with carbon capture and long-term storage (CCS)	Hydrogen produced via: • electrolysis using green electricity • biogas via SMR • biochemical conversion of sustainable biomass
Greenhouse gas emissions	High: 9 kg CO_2e/kgH_2	Depends on how efficient the carbon capture is. At 90% efficiency: 1 kg CO_2e/kgH_2	Very close to zero: 0 kg CO_2e/kgH_2

2.

Power-to-X has great climate and economic potential for Denmark

There is broad agreement that PtX will be needed to achieve full climate neutrality by 2050. Due to ambitious climate targets in Denmark and the EU, PtX will also be part of the solution towards 2030. From a technological and economic perspective, PtX is expected to play a vital role in the transformation of industry and heavy transport, in particular. At the European level, PtX will most likely be used to replace the existing use of fossil hydrogen in industry, such as the petrochemical industry, and for the green transition of long-haul heavy transport.

It is still too early to say exactly when and to what extent PtX products will contribute to the energy mix. The future role of PtX will depend largely on developments in production, technology and policy decisions, both nationally and internationally.

Despite the uncertainties, the renewable hydrogen market is expected to grow strongly by 2050, particularly accelerating after 2030, when PtX fuels are expected to become more competitive compared to fossil alternatives. Companies and nations are investing in PtX now, and have begun positioning themselves for the future hydrogen market. Denmark is well placed to hold a strong position in relation to PtX if Danish PtX initiatives are launched now.

A strong position in relation to PtX can contribute to growth and jobs in Denmark. As a pioneer in wind energy, Denmark has created growth and opportunities for many companies. Over 32,000 people currently work in the wind energy industry, and wind technology and services account for around 5% of Denmark's total exports, or more than DKK 66 billion[3].

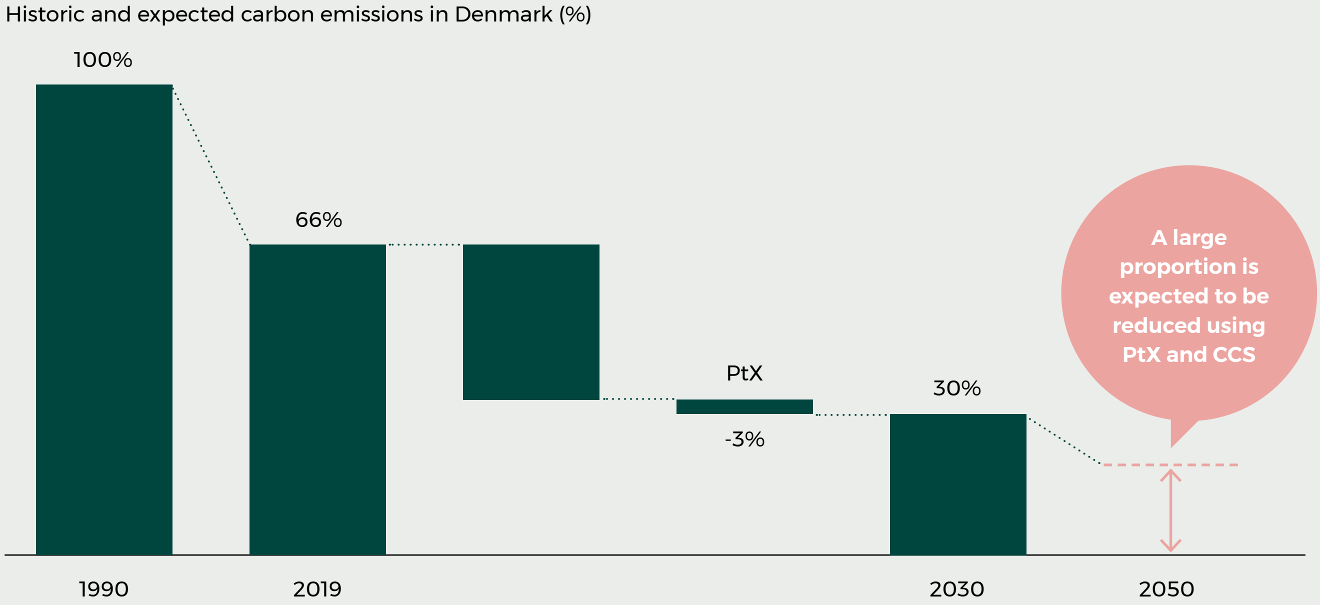
2.1. Great need for PtX in Denmark and the rest of Europe

The Danish climate partnerships indicate that PtX will have to play a key role in achieving Denmark's 70% reduction target by 2030, and in the further work towards full climate neutrality by 2050.

The report by the Danish Government's Climate Partnership for the Energy and Ulities Sector showed that electrification and other measures can take us a long way towards the 70% carbon reduction target, but also recommended that around 1.9 million tonnes of CO_2 should be reduced via PtX, to achieve the final, difficult 3% towards 2030 (see Figure 6). The analyses in the climate partnership report show that PtX is the best solution from a socio-economic perspective. If PtX is not established and in use by 2030, demands for forced electrification and carbon

[3] The Danish Energy Agency's Energy Statistics, Statistics Denmark, 'Export of energy technology and services 2019' (Danish Energy Agency, Confederation of Danish Industries, Danish Energy, Dansk Fjernvarme and Wind Denmark).

Figure 6.
Estimated PtX contribution of the energy and utilities sector to meeting Danish climate targets



NOTE: Denmark's climate target of a 70% reduction by 2030 can be achieved to a large extent through a number of electrification measures and energy efficiency improvements, but PtX will also be necessary to get across the line.
SOURCE: The energy and utilities sector climate partnership, Danish Energy, Bain & Company analysis.

Key PtX policy announcements

Government's 2020 climate programme

- PtX is expected to reduce carbon emissions from transport by 0.5-3.5 million tonnes by 2030, which will count towards the 70% target.
- After 2030, PtX is expected to reduce carbon emissions by 1.5-7.5 million tonnes, 1-4 million tonnes of which derive from international shipping and aviation. This will not count towards the 70% target.

Climate agreement for energy and industry of 22 June 2020

- Denmark has brokered a roughly DKK 1 billion deal with the Netherlands for the purchase of static shares of renewable energy. The proceeds will finance a subsidy scheme for large-scale PtX projects.
- The government will present a comprehensive PtX/CCUS strategy aimed at supporting the dissemination and development of future green solutions.
- Through its green research strategy, the government aims to launch research and development initiatives for both PtX and CCUS.
- As part of the Green Industry Forum, it has been decided to set up four new broad collaboration forums to ensure cohesion and synergies between climate initiatives, including cooperation on implementing the PtX and CCUS strategy.

will increase. Whichever solution is chosen, large investments will be required in order for Denmark to meet the target of a 70% reduction by 2030. The amount of PtX required – just to reach Denmark's 70% target – would entail an additional 10 TWh green electricity demand[4], equivalent to about 2.5 GW of offshore wind capacity. This will place great demands on the expansion of renewable energy.

After 2030, PtX is expected to play a much bigger role in achieving climate neutrality by 2050. In Denmark, direct electrification and improved energy efficiency will account for most of the carbon reductions up until 2030, while PtX and carbon capture and storage (CCS) are expected to account for most of the carbon reductions between 2030 and 2050[5]. PtX and CCS are already part of today's strategic and policy planning.

Like Denmark, the EU will also need large-scale PtX to achieve its climate targets. PtX is already part of the EU's decarbonisation plans published in the **Green Deal** (2019), **Industrial Strategy** (2020) **Offshore Renewable Strategy** (2020) and **Hydrogen Strategy** (2020), and the EU's climate targets are expected to be raised from a 40% carbon reduction by 2030, to 55-60%, increasing the need for PtX in the EU. At EU level, PtX solutions will be essential for decarbonising industry and transport, offering increased sector coupling and providing flexibility and security of supply at the same time.

2.2. PtX offers a viable solution for decarbonising industry and heavy transport

Renewable hydrogen is ideal for decarbonising the industry sector that already uses hydrogen to produce ammonia and methanol, or in refineries. In addition to industrial applications, PtX is particularly relevant in heavy transport over longer distances, in trucks, aircraft and ships. Direct electrification is not possible for much heavy transport due to the price and size of the batteries. Alternative solutions, such as PtX fuels, will therefore be needed to decarbonise the sector.

PtX products are more expensive than fossil fuels, but prices are expected to fall sharply

Renewable hydrogen and other PtX products are currently far from competitive with fossil alternatives (see Figure 7). The price difference is smallest between fossil-based hydrogen (so-called grey hydrogen) and renewable hydrogen (so-called green hydrogen), but significantly larger between PtX products such as e-methanol, e-ammonia and e-kerosene and fossil alternatives. The current willingness of consumers to pay for such green products is not enough to cover the green price differential[6].

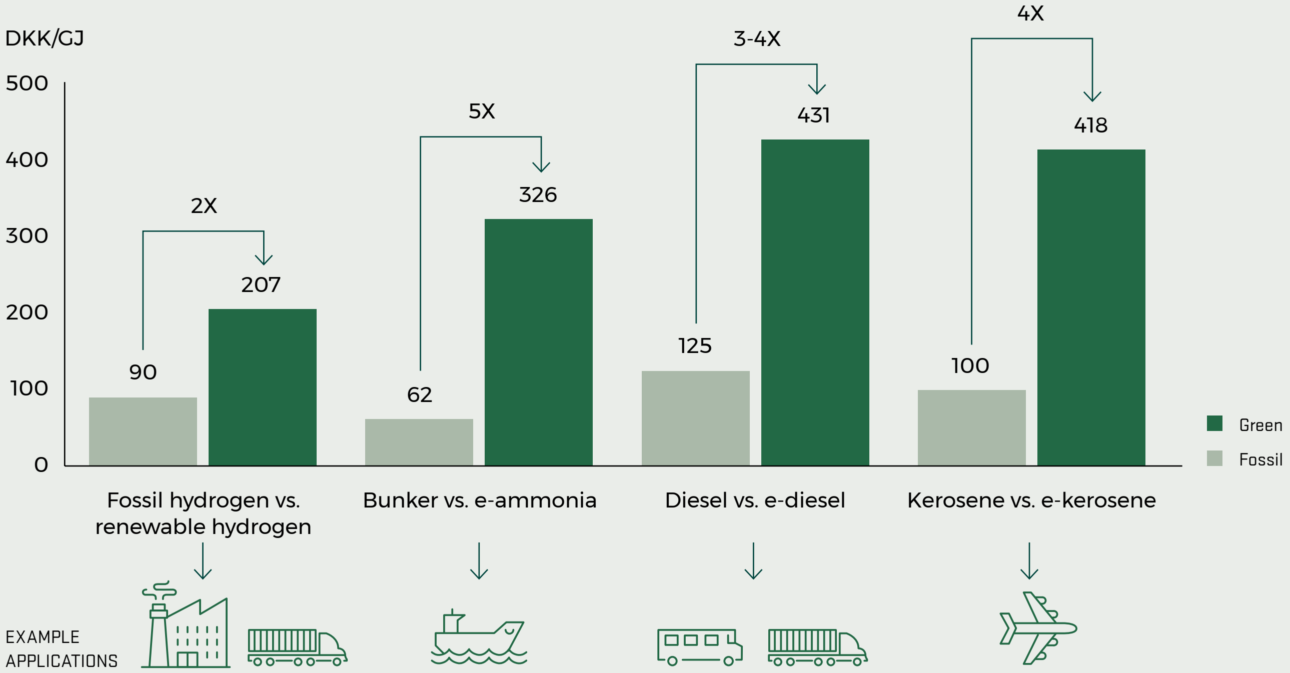
The price of electricity, including electricity tariffs, has a major impact on the price of renewable hydrogen and other PtX products (see section 1). However, the number of hours with low electricity prices is expected to rise in the future (see Figure 13).

The production costs of PtX products such as e-ammonia, e-methanol and e-kerosene are also impacted by the costs of synthesis plants. The price of these PtX products is particularly high due to low efficiency in the further processing of hydrogen. Future prices for e-ammonia, e-methanol and e-kerosene etc. will therefore be greatly affected by improvements in the efficiency of synthesis processes. Figure 8 shows that the investment costs for both electrolysis and synthesis plants are expected to fall significantly in the future. The ratio between the cost of electrolysis and synthesis plants varies for e-methanol, e-ammonia and e-kerosene, but the general expectation is a 30-50% reduction by 2030.

Estimated future prices for e-kerosene and e-ammonia are given in sections 5.4 and 5.5 respectively, taking into account the total effects of lower hydrogen costs, improved synthesis efficiency and cheaper synthesis plants.

[4] Energy and utilities sector climate partnership report.
[5] Energy and utilities climate partnership, Hydrogen Roadmap Europe, IEA, Green Deal, Hydrogen Strategy (EU).
[6] Partner companies indicate that <1% of the customer base is willing to pay a 5-10% premium across the transport sector.

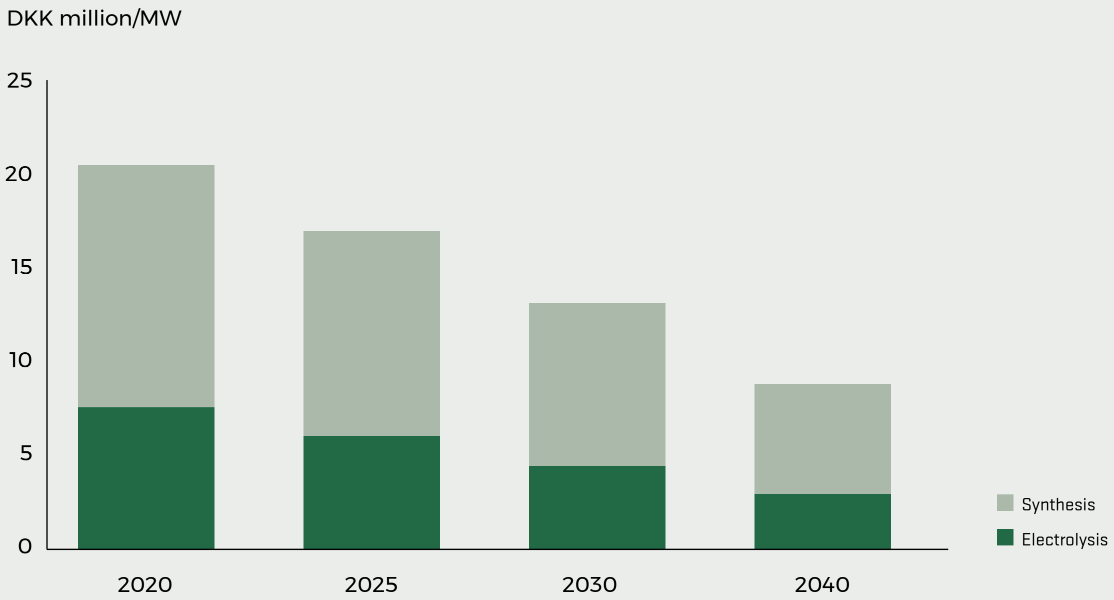
Figure 7.
Estimated prices for fossil and green fuel types in 2020



NOTE: Fossil hydrogen is defined here as hydrogen produced from natural gas using SMR without carbon capture. E-ammonia, e-diesel and e-kerosene are based on renewable hydrogen.

SOURCE: Ea Energianalyse, BloombergNEF, The Danish Energy Agency's macroeconomic consumer prices, Hydrogen Council, Danish Energy, Bain & Company analysis.

Figure 8.
Construction costs for a methanol processing plant, split between electrolysis and synthesis



SOURCE: Ea Energianalyse, Danish Energy.

Renewable hydrogen is expected to become competitive in chemical industry and heavy road transport by 2025-2035

The price of renewable hydrogen is expected to fall significantly by 2030[7], achieving price parity with fossil hydrogen by around 2030 (see Figure 9). A number of analyses of the price trend for renewable hydrogen have been done. There are big differences in the price levels in the analyses, but many of them point to renewable hydrogen reaching price parity with fossil hydrogen around 2030 – including the analysis behind the EU hydrogen strategy. The trend is being driven by falling electricity prices due to the planned RE expansion, better electrolysis plant efficiency and an improved regulatory framework for sector coupling (see section 5.2 on the production of PtX). The timing of price parity will also be affected by whether CO_2 emission allowances are allocated in the future to fossil and renewable hydrogen.

Fossil hydrogen currently receives free CO_2 allowances under the EU's Emissions Trading System (ETS), while renewable hydrogen is not allocated allowances. The European Commission has announced that it is looking into how to deal with the issue going forward. One possibility is that fossil hydrogen will stop receiving free allowances in the future and thus have to factor in an allowance price. The possible effect of this is shown in Figure 9, as a significant increase in the price of fossil hydrogen.

The price of low-carbon hydrogen is calculated as the price of fossil hydrogen produced using natural gas, plus a fixed premium[8] for CCS and a small amount for a rising CO_2 allowance price, equivalent to around 10% carbon emissions (for what is not captured by CCS). Low-carbon hydrogen may serve as an alternative to renewable hydrogen during a transition period, but is not expected to be competitive in the long term.

The use of hydrogen as a fuel is limited in existing Danish industry. The potential for hydrogen in industry is expected to be greatest in countries with heavy industry, such as Sweden, Germany and the Netherlands. The first sectors expected to convert to PtX fuels are chemical industry and heavy road transport, and both are expected to use renewable hydrogen.

In Denmark, there is a potential to use renewable hydrogen in refineries and for heavy transport. In heavy road transport, use in trucks is considered to hold the greatest potential. Long routes with heavy freight are expected to convert to hydrogen trucks (FCEV[9]), as the total cost of ownership is expected to be lower than for trucks powered by an internal combustion engine, provided that a number of conditions are met. The expected improvement in the competitiveness of hydrogen trucks will primarily be driven by an expected drop in the price of renewable hydrogen, lower maintenance costs for electric motors and a drop in the price of hydrogen trucks when major automakers launch models from around 2023. However, the infrastructure will have to be in place and potential imbalances in taxes must be eliminated. Other PtX products, such as e-methanol, e-diesel, e-petrol and e-dimethyl ether (DME), are also expected to play a role in heavy road transport, especially during a transition phase.

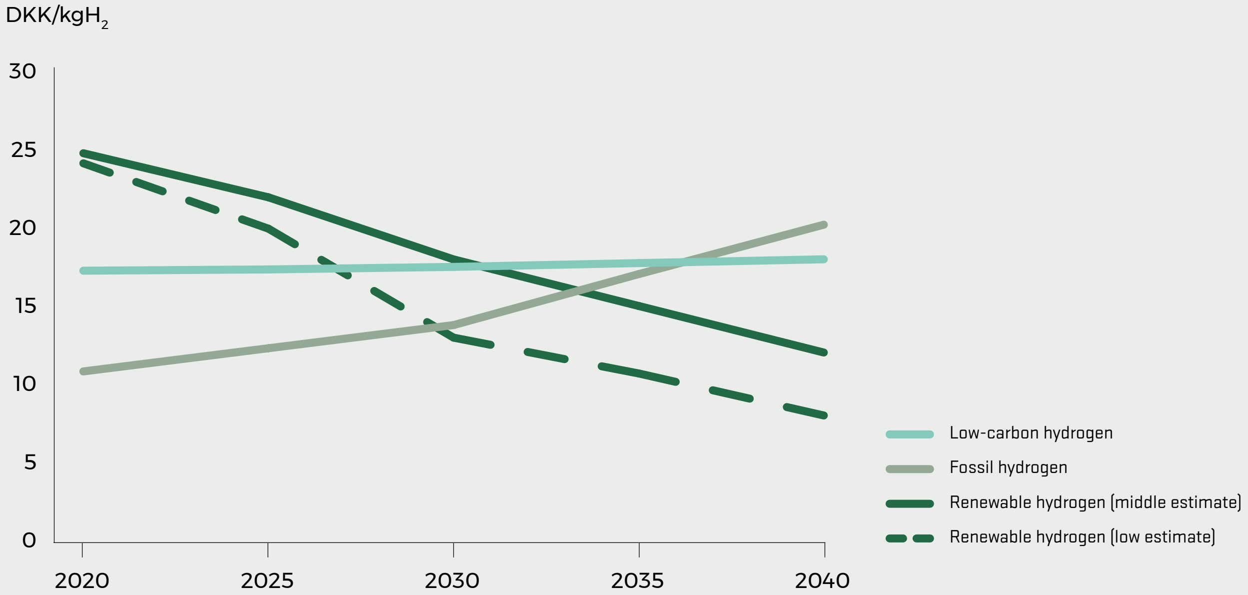
It is uncertain when industry and heavy road transport will convert to renewable hydrogen. This will depend on developments in the production of renewable hydrogen, the necessary infrastructure, hydrogen trucks, carbon allowances and the willingness of consumers to pay a 'green' premium.

[7] Ea Energianalyse, Danish Energy, Bain & Company analysis.

[8] The low-carbon hydrogen price is based on SMR technology, including natural gas cost + approx. 1 USD/kg hydrogen for CCS in 2030. (source: Ea Energianalyse). The premium on the CCS portion of the low-carbon hydrogen price is subject to considerable uncertainty. A significant change in the cost of CCS or an alternative production method could potentially lower the price of blue hydrogen in the future.

[9] Fuel Cell Electrical Vehicles – hydrogen is converted to electricity in fuel cells to power an electric motor.

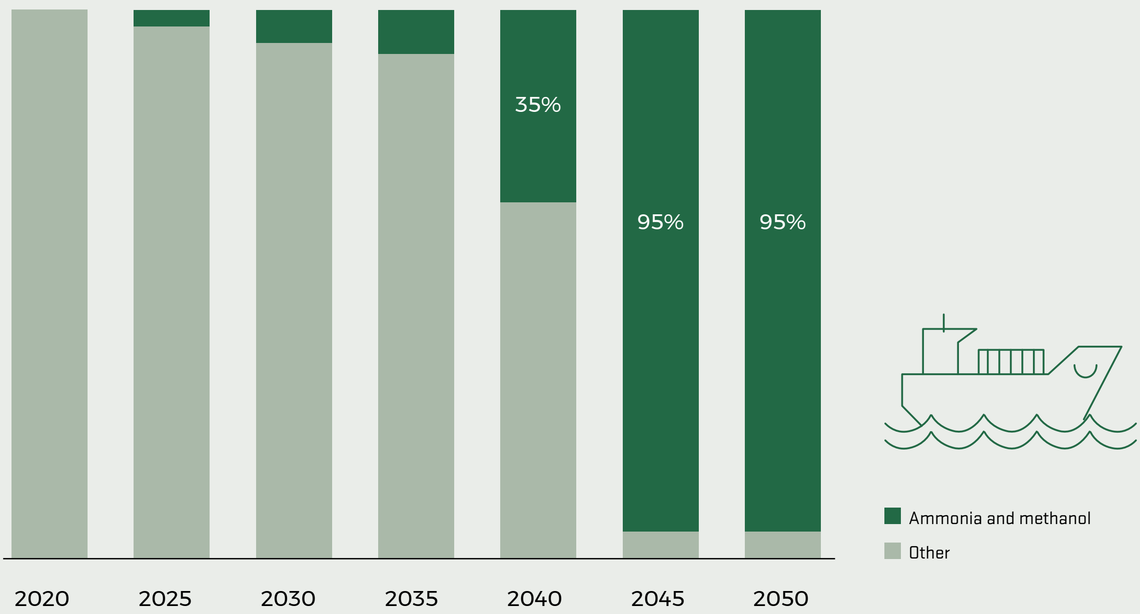
Figure 9.
Estimated price trend for fossil, low-carbon and renewable hydrogen



NOTE: Price range for renewable hydrogen based on EA Energianalyse's estimate for hydrogen production in Denmark in 2020-2040, based on the Balmorel model. See further explanation for the middle hydrogen price estimate in Figure 24.

SOURCE: Ea Energianalyse (renewable hydrogen price), Danish Energy Agency macroeconomic consumer prices, Danish Energy, Bain & Company analysis.

Figure 10.
Expected share of PtX in global shipping, %



NOTE: The proportion of ammonia and methanol used in shipping may increase as shown in this figure, in order to meet the IMO goal of a 50% reduction in carbon emissions by 2050.

SOURCE: Journal of Marine Science and Engineering, DNV-GL, Energy Transitions Commission, Danish Energy, Bain & Company analysis.

Green PtX fuels are expected to be competitive in aviation and shipping after 2030

Aircraft can technically already use e-kerosene, as it is identical to fossil kerosene, but costs are about four times as high (see Figure 7). Lower e-kerosene prices must primarily be driven by lower renewable hydrogen costs, which are expected to fall significantly (see Figure 9). It will take time and require production to be industrialised for green fuels to come closer to price parity with fossil fuels without any support or regulatory intervention. Price parity is not expected until after 2040 (see section 5.4), but since e-kerosene does not require new aircrafts or infrastructure, it could be an area where demand rapidly escalates. In addition to decarbonisation using e-kerosene, aircraft manufacturers are investing in the development of electric and hydrogen-powered aircraft. Development is still at a very early stage, and the aircraft will potentially only be on the market from 2035[10].

In shipping, the technology has not yet been determined. E-methanol and e-ammonia can eventually be used as fuel, but this will require the conversion of existing ships, and a complete new fleet and the construction of port infrastructure. A few ships are currently methanol-powered, and the first ammonia-powered ship is expected to be ready in 2024. Use of PtX in shipping lacks technological maturity, and lower costs for renewable hydrogen for the production of e-methanol and e-ammonia will be necessary. The market for e-methanol and e-ammonia in shipping is not expected to take off until 2035-2045, when the IMO's current requirement of a 50% reduction by 2050 will accelerate the transition[11].

General uncertainty for PtX in industry and heavy transport

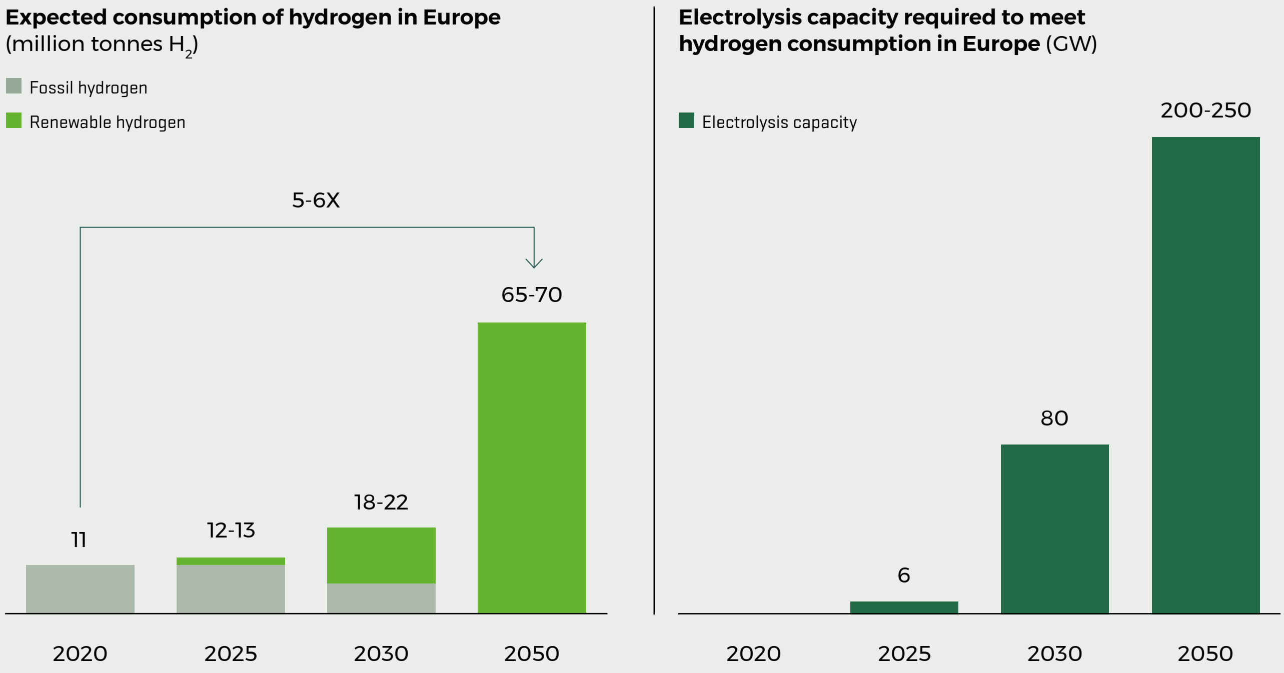
In addition to the uncertainties on the demand side for PtX products, such as the technological development of trucks, aircraft and ships, there are also a number of general uncertainties. It is still uncertain which green fuels will end up being the most competitive, and the outcome will place different demands on production and infrastructure. PtX production can be centralised (where green electricity is produced) or decentralised (close to the end-user). Uncertainty about where production and demand will be located means that hydrogen infrastructure has to be developed gradually, with the possibility of continuous adjustment and adaptation. The key uncertainty regarding the competitiveness of PtX products is the learning curve for electrolysis plants, which need to reduce construction costs and increase efficiency. While it is difficult to know exactly which PtX products will end up being chosen and when they achieve full competitiveness, there will clearly be a great need for renewable hydrogen in the future, as it serves as the building block for all of them.

2.3. The market for PtX and renewable hydrogen in Europe is expected to grow dramatically

Hydrogen consumption in the EU is expected to increase five or six fold by 2050, in step with an increase in renewable hydrogen production (see Figure 11). The trend will accelerate in the 2030-2050 period, when hydrogen consumption quadruples. The rise in hydrogen consumption will be particularly due to the use of PtX products in heavy transport (see section 2.2). Increasing use of renewable hydrogen as a means of achieving climate targets in Denmark and the EU will continue to place greater demands on electrolysis capacity (see Figure 11), and an exponential increase is expected towards 2050. The EU has a goal of producing 10 million tonnes of renewable hydrogen by 2030 (equivalent to 40 GW of electrolysis capacity) and of importing an additional 10 million tonnes of renewable hydrogen[12].

[10] Airbus ZEROe concept aircraft.
[11] Journal of Maritime Science and Engineering, DNV-GL, Energy Transition Commission.
[12] Hydrogen Roadmap Europe.

Figure 11.
Expected future European demand and production capacity for renewable hydrogen



NOTE: The EU estimates that 40GW electrolysis can produce 10 million tonnes of hydrogen, assuming that the electrolysis plants are in full operation throughout the year.
SOURCE: Hydrogen Roadmap Europe; Institute of Energy Economics and Financial Analysis (IEEFA.org), International energy agency, IEA, Danish Energy, Bain & Company analysis.

Figure 12.
Overview of country targets for renewable hydrogen production and funding

	Hydrogen production	Allocated funding
EU	6 GW in 2025 and 40 GW in 2030	DKK 180-310 billion
Germany	2 GW in 2025 and 5 GW in 2030	DKK 67 billion
The Netherlands	0.5 GW in 2025 and 3-4 GW in 2030	DKK 375 million annual funding
France	6.5 GW in 2030	DKK 53 billion
Portugal	2.0 GW in 2030	approx. DKK 7 billion
Korea	1.5 GW in 2022 and 15 GW in 2040	DKK 25 billion by 2030
Japan	15 GW in 2040	Subsidy on the purchase of hydrogen cars
Australia	No specific GW targets	DKK 1.7 billion

SOURCE: Hydrogen strategy for the EU, Germany, Netherlands, France, Korea and Japan, Danish Energy, Bain & Company analysis.

To meet the EU's projected renewable hydrogen needs by 2050, 200-250 GW of electrolysis capacity must be established, equivalent to around 400 GW of offshore wind capacity. The current electrolysis capacity under construction in Denmark is 34 MW.

The world is investing in Power-to-X now

Private investors see a potential in PtX, as can be seen by the fact that the market value of companies focusing on renewable hydrogen has increased 300-500% over the past 18 months[13]. PtX products have also received more attention among business leaders. In a 2020 survey of top executives in the oil and gas industry, 42% said their company would be investing in the hydrogen industry during 2020[14]. This compares to 20% in 2019. Many large energy companies, such as Shell, Ørsted and Vattenfall, have chosen PtX as a strategic focus area[15]. Countries both inside and outside Europe have already defined strategies for PtX production and infrastructure, and allocated large sums to support the transition (see Figure 12).

In particular, countries such as Germany, the Netherlands and France have allocated large amounts of money to support the establishment of PtX production and infrastructure. National strategies can help provide clarity for businesses, giving them a more solid basis for investing in PtX.

2.4. Denmark is well placed to claim a strong position in the field of PtX

Access to competitive green electricity on a large scale

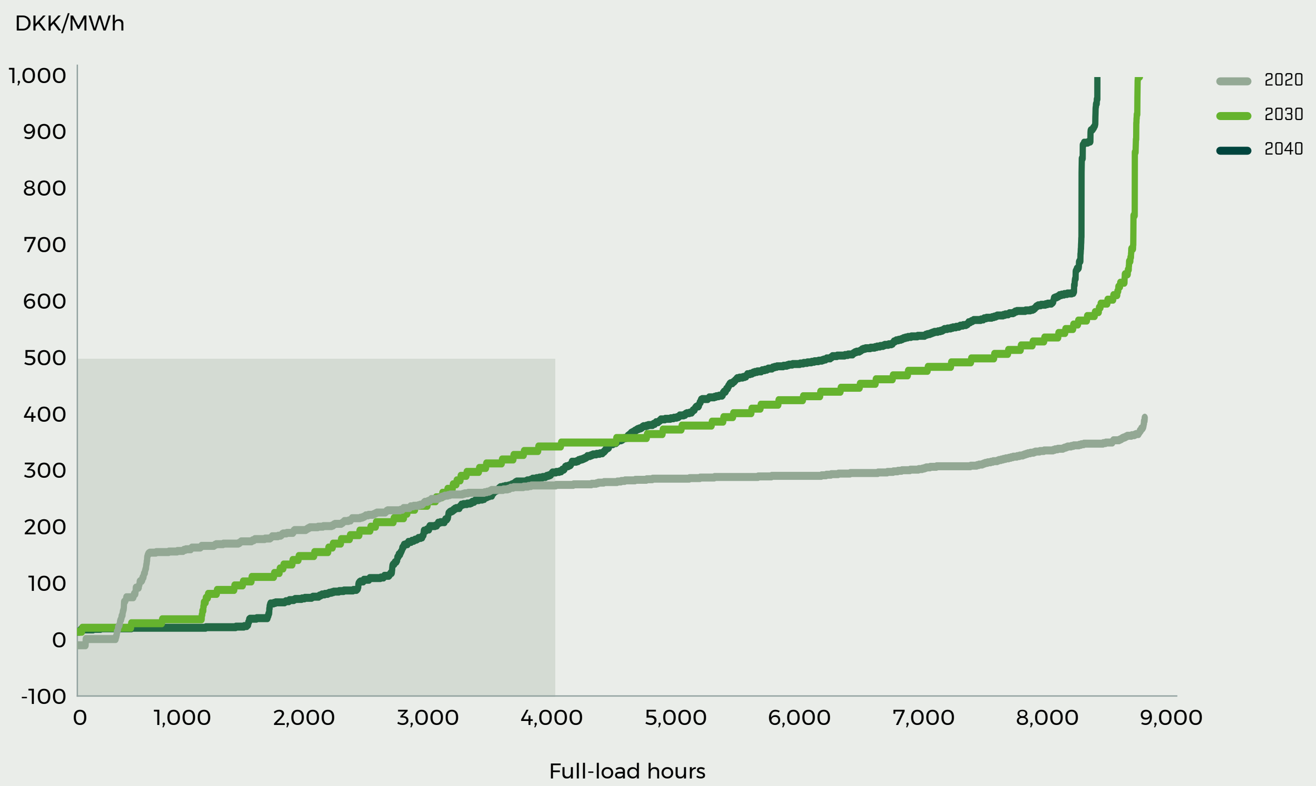
Competitive electricity prices are a crucial factor in being able to produce competitive renewable hydrogen, as electricity currently accounts for around 50% of the total production costs (see Figure 4). Denmark can produce competitive green electricity, and the levelised cost of energy (LCOE)[16] for solar and offshore and onshore wind power is already lower than for electricity produced using fossil fuels such as gas and coal[17]. In Europe, wind energy has an average LCOE 10-15% lower than large-scale solar power, and is therefore still the cheapest form of production[18]. Denmark has good wind resources, and several attractive regions for the expansion of offshore wind. Under current political restrictions, 40 GW of offshore wind can be built on the Danish shelf, while the total technical maximum is estimated at around 180 GW[19].

An electrolysis plant with flexible production can take advantage of the cheapest hours, reducing the electricity costs. Cheap green electricity is essential in order for Denmark to be competitive in renewable hydrogen production. A growing proportion of green power in electricity generation will lead to greater fluctuations in electricity prices, and hence more hours with low electricity prices. The duration curve for electricity prices in Denmark (Figure 13) shows more hours with low electricity prices in the future, which will make hydrogen production cheaper. A simulation of the spot price for electricity in Denmark by Ea Energianalyse shows significantly more electricity price variation in the future.

The investment cost for electrolysis plants is also expected to fall significantly (see Figure 8). This means it will be profitable to produce hydrogen with significantly fewer operating hours in the future. Overall, this will cause the total cost of hydrogen production to decrease significantly in Denmark, as shown in Figure 9 above.

[13] Plug Power, ITM, Powecell, Ballard.
[14] DNV GL, Heading for Hydrogen, the oil and gas industry's outlook for hydrogen, from ambition to reality 2020.
[15] Examples: Shell project NortH2, Ørsted project Gigastack, Vattenfall project Hybrit.
[16] The levelised cost of energy reflects the total lifetime cost in relation to the amount of energy produced.
[17] For newly built production capacity – Danish Energy Agency (2019).
[18] IRENA: Renewable Power Generation Costs in 2018.
[19] Energy and utilities sector climate partnership report.

Figure 13.
Significantly more hours with low electricity prices by 2030 and 2040



NOTE: The figure shows the duration curve in 2020, 2030 and 2040. It shows hourly electricity prices in Denmark, sorted from the lowest to the highest prices. Electricity prices have been calculated using the Balmorel model. The lowest hydrogen price derives from an electrolysis plant with approx. 8,000 full-load hours/year in 2020, dropping to 6,000 hours/year in 2025 and about 4,000 hours/year in 2030 (leading to a settlement price for electrolysis of around DKK 170/MWh).

SOURCE: Ea Energianalyse, Danish Energy.

Denmark has a good geographical position for exporting renewable hydrogen
North-west Europe, particularly the Netherlands and North Rhine-Westphalia in northern Germany, is expected to become a centre for renewable hydrogen in Europe. The region has hydrogen-intensive industry, access to the North Sea and good existing gas infrastructure. The Netherlands and Germany are considering converting parts of this infrastructure to transport hydrogen. Both countries also have ambitious strategies in the region, and are politically proactive in terms of regulation and collaboration agreements[20]. France has also laid out an ambitious strategy in this area (see Figure 12) and, together with Germany and the Netherlands, could become an attractive export market. Based on the expected hydrogen consumption and production in 2030 reported for the three countries, there should be a potential to export around 1.9 million tonnes of renewable hydrogen (see Figure 14). This volume of hydrogen has a market value of approx. DKK 65 billion.[21] Other nearby hydrogen markets may also hold potential for export, such as Gothenburg in Sweden.

Close proximity to export markets may give Denmark a competitive edge, as transport costs may prove decisive in the competition to produce cheap renewable hydrogen (see Figure 15). There will be competitors from other countries in the export markets, who may be able to produce renewable hydrogen with low production costs using cheap green electricity. However, there will be an additional cost to convert hydrogen to liquid hydrogen, ammonia or the like, and a transport cost that depends on the distance. Denmark can gain a competitive advantage in the export of hydrogen to nearby countries if a hydrogen pipeline is established, as this has significantly lower transport costs and does not require any conversion[22].

Denmark may also be able to export liquid PtX products such as e-ammonia and e-methanol, if Danish production is competitive and there is sufficient demand. All elements for transporting and trading in ammonia already exist, as ammonia is used in fertilizer around the world.

There could be close competition between e-ammonia produced in Denmark using plentiful wind resources and e-ammonia produced in sunny areas such as North Africa, as future production costs are expected to be at the same level (see Figure 16). The future trend for the ammonia price is further described in Figure 31.

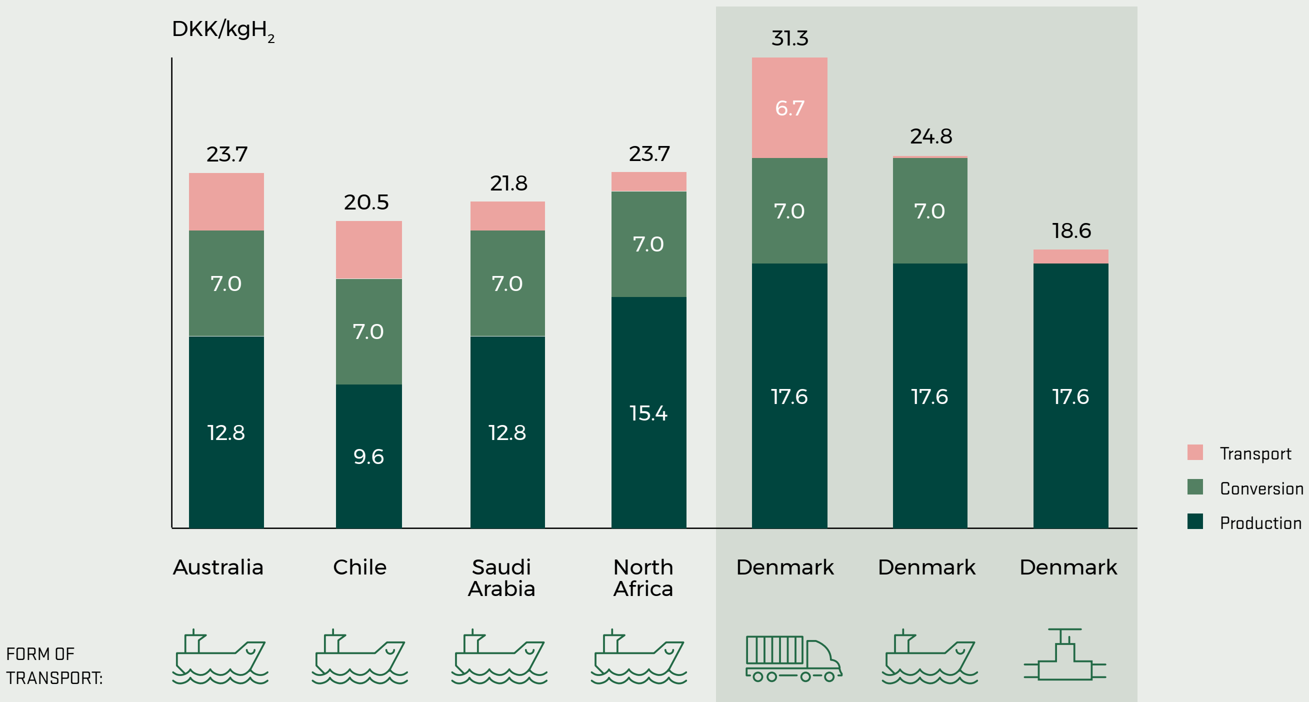
Denmark has a world-class energy system, within which sector coupling can lower the price of PtX
In addition to competitive green electricity production and a good geographical location for export, the Danish energy system has been acclaimed as the best in the world[23]. This acclaim is due in part to high security of supply and a highly cohesive energy system. Interplay between the elements of the Danish energy system (electricity system, gas system and district heating), provides good conditions for sector coupling, which can reduce the total cost of PtX production in Denmark. For example, heat from electrolysis and synthesis plants can be used in the district heating system, reducing the cost of PtX products and increasing energy efficiency. Sector coupling is illustrated in Figure 17.

[20] Forbes, Thyssengas, World Financial Review.
[21] The expected production cost of renewable hydrogen in 2030 has been used as a proxy for price (DKK 22/kgH_2), see section 5.2.
[22] Hydrogen must be converted from gas to liquid for shipping.
[23] The World Energy Council and the International Energy Agency.

Figure 14.
Estimated need for renewable hydrogen imports in north-west Europe

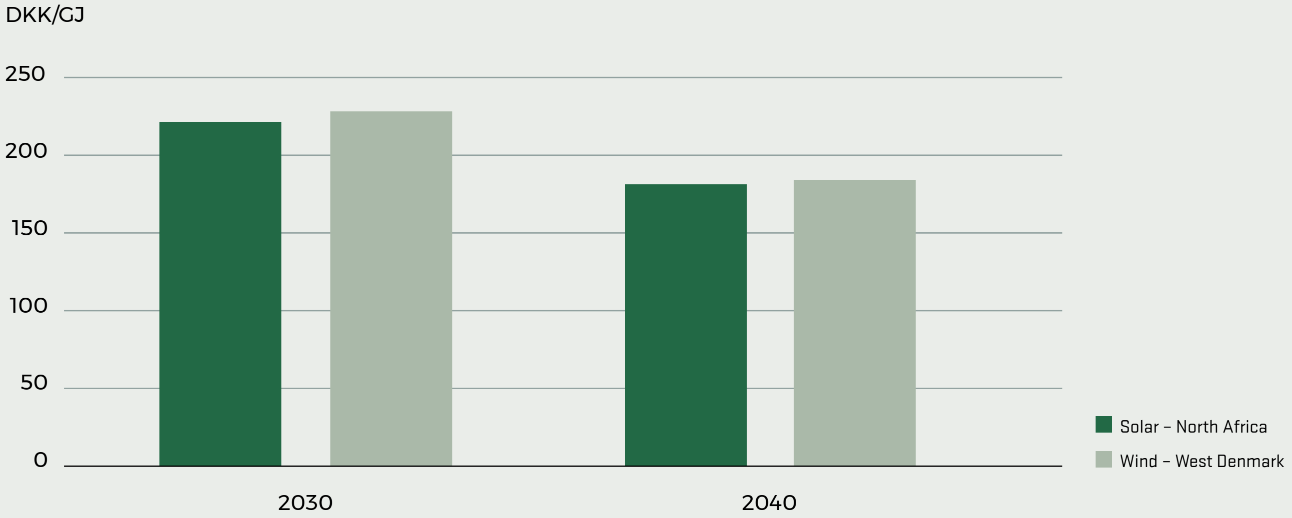
NOTE: Hydrogen strategy for Germany, the Netherlands and France.
SOURCE: Danish Energy, Bain & Company analysis.

Figure 15.
Estimated cost of renewable hydrogen exports to Rotterdam in 2030



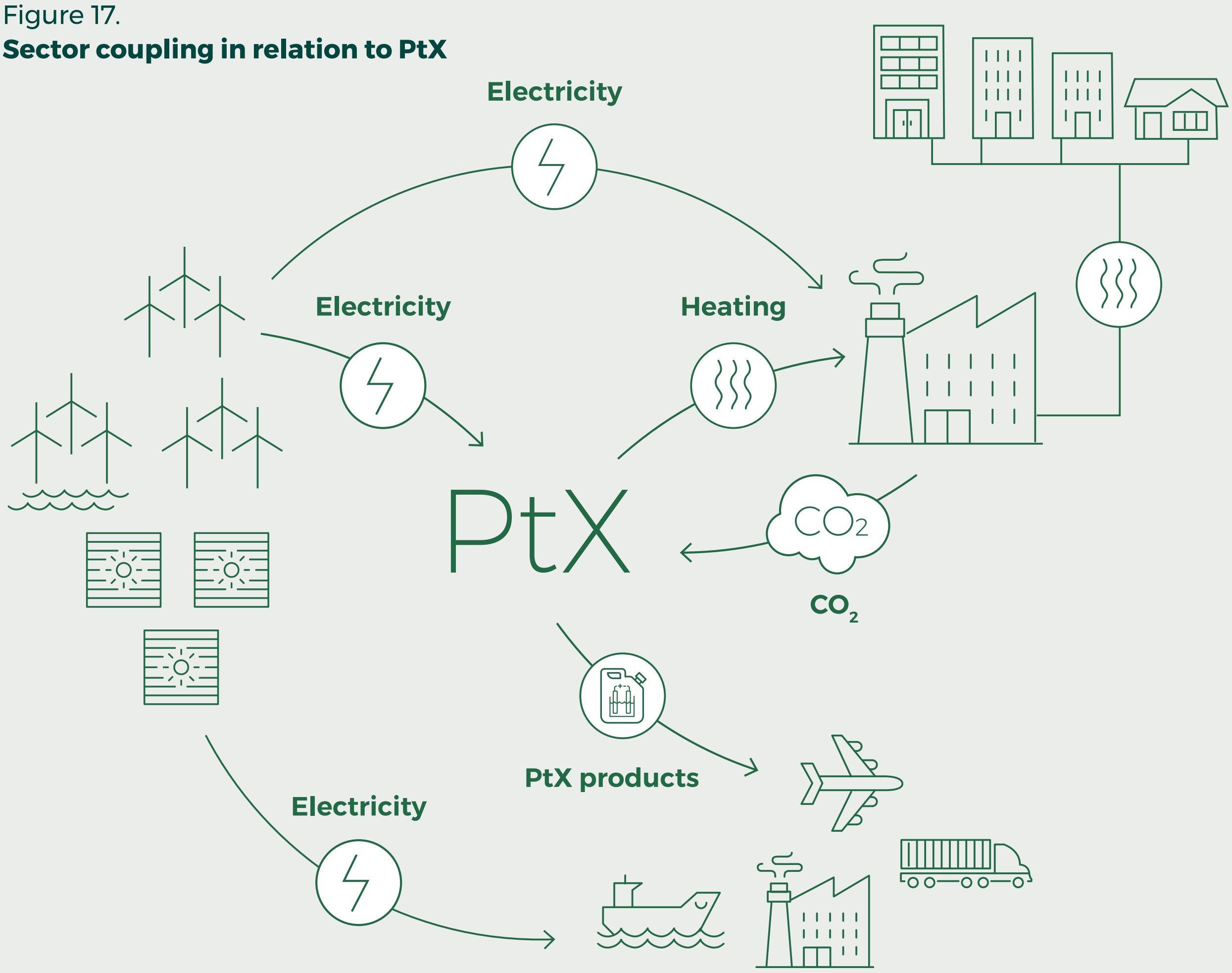
NOTE: Conversion costs are the same in all countries. Production costs in Denmark exclude tariffs, to be comparable with LCOE from other countries. Transport costs by ship are based on the direct distance to Rotterdam. The distance for a tanker from Denmark is 350 km.
SOURCE: European Commission, Ea Energianalyse, European Hydrogen Backbone Report, Danish Energy, Bain & Company analysis.

Figure 16.
Production costs for e-ammonia in Denmark compared to North Africa



SOURCE: Ea Energianalyse.

Figure 17.
Sector coupling in relation to PtX



3.
Key considerations for Power-to-X in Denmark

PtX will be crucial in addressing the national and global climate challenges, but Denmark faces a particular challenge, as consumption depends on available supply from production, and production depends on sufficient demand from consumption – and neither currently exist. This structural paradox, illustrated in Figure 18, must be addressed in order to get PtX off the ground in Denmark.

Without subsidies or other incentives, the consumption side will only demand the new green PtX products and make the necessary technology choices when the product prices are competitive.

PtX products will only become competitive when production is sufficiently industrialised and scaled up. Production will only begin to be industrialised and scaled up once there is a guaranteed demand – i.e when consumers demand or commit to purchasing the products. We call this the PtX paradox.

Initiatives are needed to help address the PtX paradox, so we can kick-start the production and use of PtX products.

Other countries are already underway. They have also seen the need for a massive expansion and industrialisation of PtX – to address climate challenges, but also to reap the commercial benefits of building an industry to service the world's climate needs.

We are therefore at a crossroads, where we can either be content being a supplier of green power, leaving PtX production to others, or we can take part in the industrialisation and help build up competences in this field.

It is our conclusion that we should invest in Denmark becoming richer, by not only exporting power, but also the green energy resources of the future in the form of PtX products.

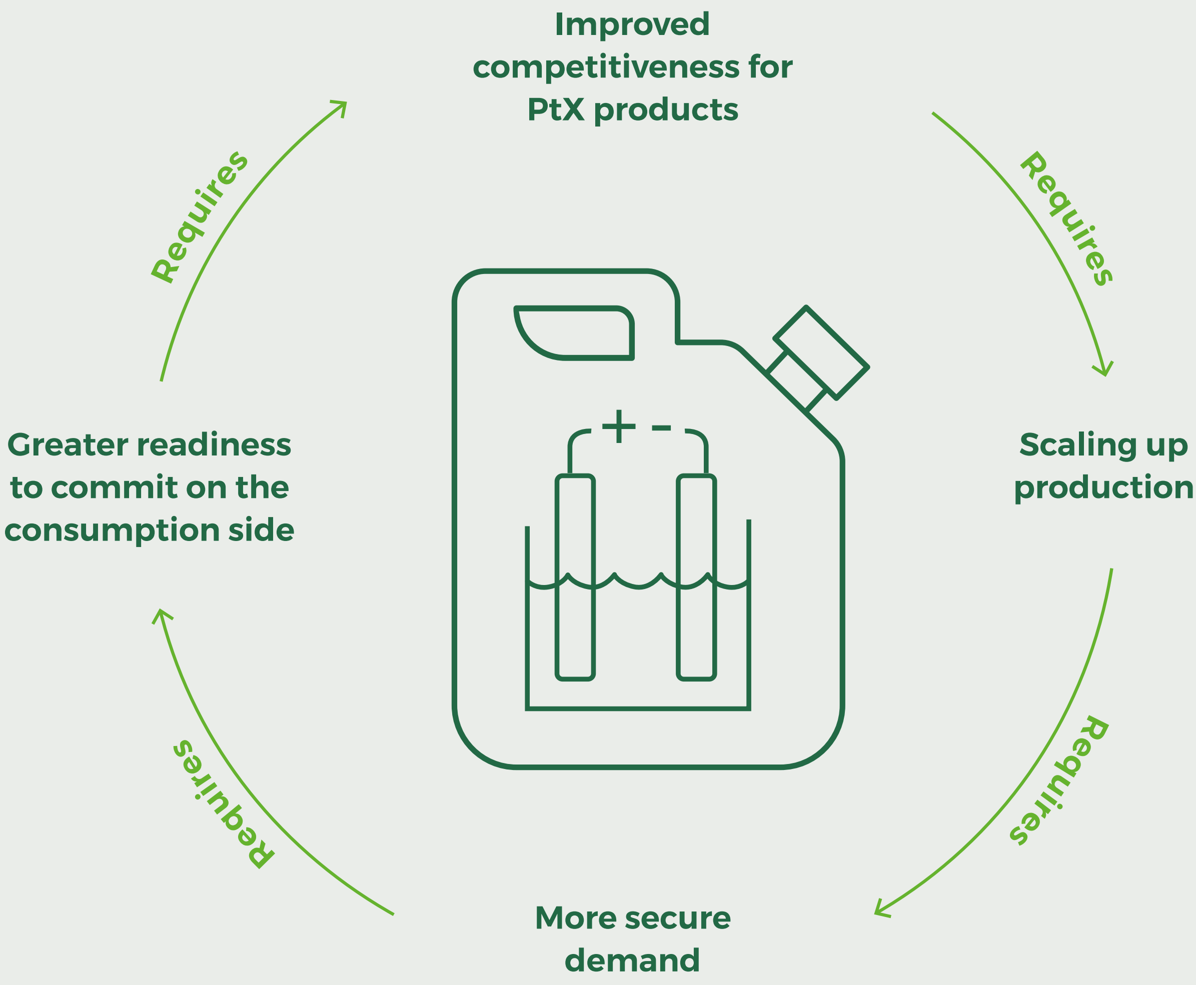
In order to succeed, there are five key considerations that need to be taken into account when laying out a Danish PtX strategy.

1.

National demand cannot drive industrialisation alone – both a national and an international strand is needed

Denmark is a small market overall. In relation to the development of PtX the Danish market is currently even smaller, as we do not have any significant hydrogen-consuming industry. Denmark therefore cannot pursue an industrialisation strategy based on national demand alone. In the short term, the large demand for renewable hydrogen lies in our neighbouring countries to the south, and consumption is thus driven by international frameworks and direction. The same is true of the transport sector's need for PtX products, which are largely defined by European and global markets. Denmark is therefore highly dependent on EU regulation and international collaboration. This is necessary in order to set the framework for green demand, which can create a level playing field for businesses and thereby increase the global willingness to pay. It is also necessary in order to define European and global market frameworks for infrastructure and trade in PtX products. The strategy must therefore have both a national and an international strand.

Figure 18.
The PtX paradox



SOURCE: Danish Energy, Bain & Company analysis.

2.

Denmark has a small, open economy with foreign competition – measures must therefore be chosen carefully to ensure that Danish companies are not disadvantaged compared to foreign ones.

As a small open economy, import and export of goods and services is necessary for Denmark. The requirements imposed on Danish companies will determine whether they can survive in an international market. Special national legislation with strict climate requirements or high taxes could lead to significant risk, which could harm Danish competitiveness and lead to increased imports at the expense of Danish-produced goods and services and ultimately to the relocation of production and Danish companies. This would first of all mean the loss of Danish income and jobs, but also missing out on the intended climate benefits, because activities and consumption are simply moved outside Denmark. Measures must therefore be designed wisely, so that they do not put Danish companies at a competitive disadvantage to foreign ones. This may mean, for example, that requirements to ensure demand are combined with supporting initiatives. If Denmark successfully kick-starts its PtX efforts, Danish companies will be able to get a green head start. This applies not only to the companies that export the green solutions needed for PtX production, but also to the companies that purchase PtX products.

3.

Confidence about the ability to obtain PtX products is essential for the consumer's choice of technology. Timely expansion of production capacity is therefore essential and requires investment in order to create demand

Both price and availability are crucial to consumers of PtX products when they have to make technology and consumption choices. The conversion rate on the consumption side is faster than the necessary development of RE and electrolysis capacity (see Figure 19). If the PtX expansion happens too late, bottlenecks and delays in the green transition may occur. Conversely, demand can more easily catch up if production is expanded ‘too rapidly’ (see Figure 19). Renewable hydrogen which is not sold on the domestic market can be exported to other markets such as Germany and the Netherlands. Timely expansion of production capacity is therefore necessary, which requires decisions and investment before demand is fully in place.

4.

We have demonstrated the technology, but not on an industrial scale. The next step is therefore large-scale projects to industrialise PtX and improve its competitiveness with fossil alternatives

We are familiar with the technologies, and the first step towards 2030 is therefore to kick-start both supply and demand on an industrial scale. This will best be driven by the business sector. Research can and must support the industrialisation process, by refining production technologies and the use of PtX fuels, and building skills and attracting skilled candidates and experts who can work in the industry. Research cannot secure investment in PtX or reap the benefits of industrialisation. Implementing the technology on a large-scale optimises and adapts it to industrial operations, while driving down costs and improving competitiveness. Research is therefore needed to support the future PtX industry and its development, but other measures are also needed to kick-start the necessary large-scale projects.

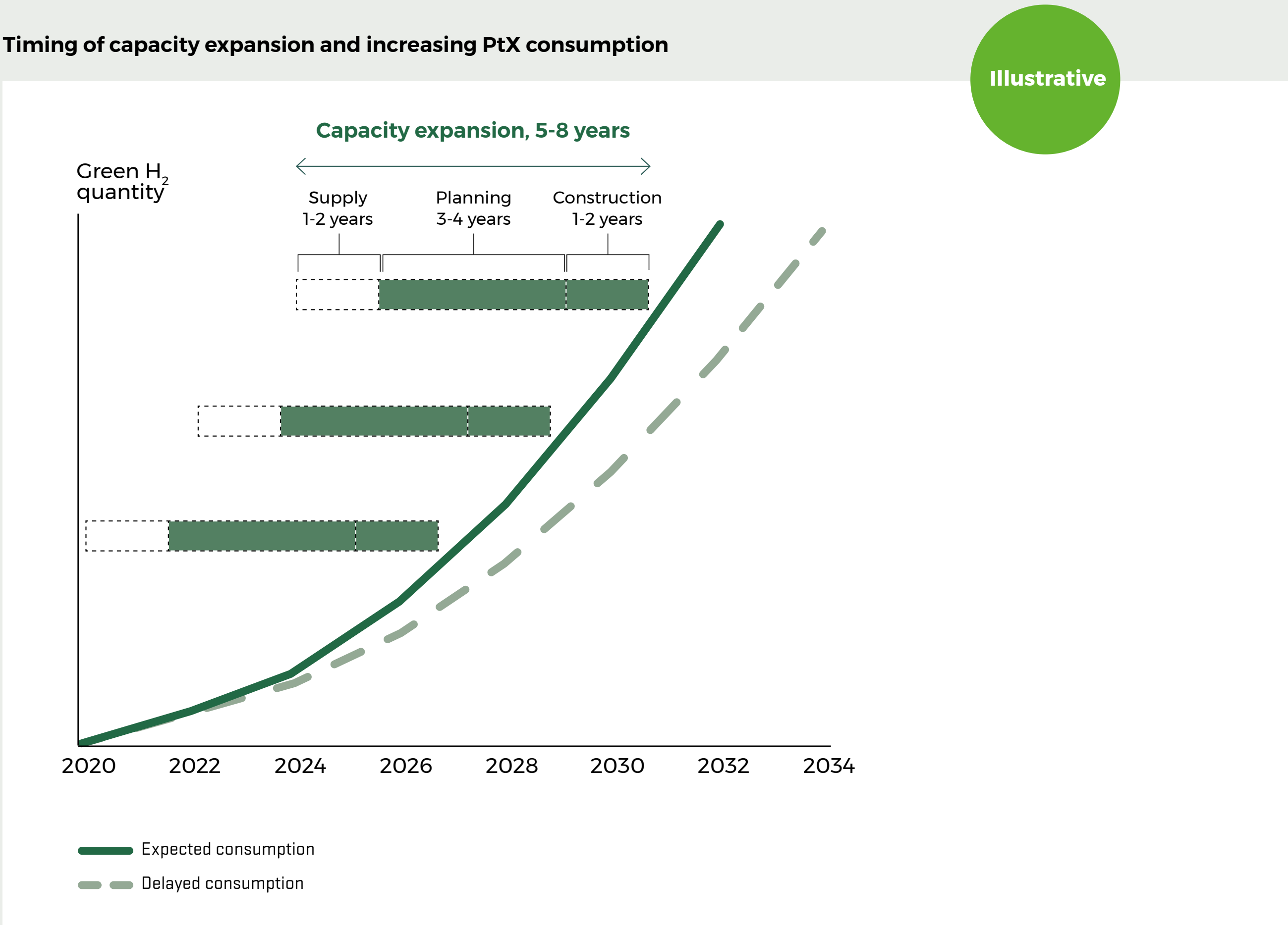
5.

The technological and market risks are numerous. These must therefore be shared by private investors and society until PtX fuels are competitive

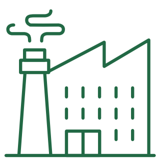
There are many unresolved issues, uncertainties and variations in relation to the production, distribution and consumption of PtX products. The learning curve for electrolysis, in relation to both establishment and operation, will affect the price of PtX products. What PtX products and technologies will be matured and at what pace, remains to be seen. The shape of the market will continually change, as PtX production can take place centrally (close to green electricity production) and decentrally (close to PtX consumption), which will influence the need for infrastructure among other things. Overall, investors face many substantial risks. If these risks are not adequately hedged, capital will seek areas with greater security. It is therefore essential for investment in PtX, and hence also industrialisation, that risks are shared between investors and society until PtX products are competitive.

Figure 19.
PtX capacity expansion and technical conversion rate for consumption segments

Timing of capacity expansion and increasing PtX consumption



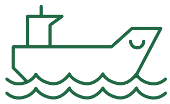
Technical conversion speed



1-2 years.
Full compatibility with current processes and infrastructure.

4-6 years.
Requires new vehicles. Diesel trucks are typically written off over 5 years.[2]

1-2 years.
Full compatibility with current processes and infrastructure.[1]



15+ years.
Requires a new fleet. Container ships are typically written off over 25-30 years.[2]

NOTE: [1] The most recent large offshore wind farm, Horns Rev 3, took seven years to build, from the date the Folketing approved construction until it was ready for operation.
[2] Infrastructure needs to be converted for heavy road transport and shipping, but this is not deemed to be a limiting factor for the rate of conversion.
SOURCE: Energy Agreement 2018, expert interviews, Danish Energy, Bain & Company analysis.

4.

An ambitious and agile Danish PtX strategy

Denmark faces a great opportunity with PtX if we are able to exploit Denmark's strengths and deploy the right measures in the strategic work. PtX can contribute to addressing the Danish and global climate challenges, while creating significant economic growth for Denmark. Supply and demand need to be developed in parallel to avoid bottlenecks in PtX development and the green transition. The countries around us are underway, so we need to act now.

The Folketing must pave the way for Denmark to lay the foundations for a new green industry within six months. This means that the government and a majority in the Folketing have to adopt an ambitious and agile PtX strategy covering the entire value chain, from production to the use of PtX products. The government must set aside around DKK 10 billion between 2021 and 2030 to kick-start and industrialise PtX production, and support technology change in the sectors that will be using PtX products.

Danish companies are well placed to establish a strong PtX position, and an ambitious Danish PtX strategy is needed to exploit this potential. It is also important that the PtX strategy creates greater investment certainty for private actors, by clarifying plans for changes in regulation, tenders and subsidy models, as well as infrastructure development. The strategy should be two-pronged, focusing on both the national and international arena. The national focus areas must kick-start the Danish PtX industry in the short term, while the international focus areas must ensure long-term development and demand. The focus areas, combined with a clear governance structure, must ensure that the Danish PtX ambition is realised, as illustrated in Figure 20.

Figure 20.
An ambitious and agile PtX strategy with four key components

Ambition

- An ambitious PtX programme to ensure that Denmark's major strengths in relation to PtX are exploited, to help make Denmark fossil-free and contribute to the global green transformation through the export of energy and technology
- This ambition has to support a reduction of 2.5 million tonnes in carbon emissions in Denmark by 2030

National action

- Kick-start the Danish PtX efforts through subsidies and regulation
- Establish the structural basis for full industrialisation of PtX products. Focus on the production of PtX products with a view to reduce costs
- Maturation of the buyer side and increase demand for PtX products

International action

- Implementation of rules and frameworks for an international market where the value of renewable hydrogen is clear
- Boost international demand for PtX to avoid a decline in the competitiveness of Danish companies and to create a market for Danish PtX products and technologies

Dynamic governance

- PtX requires a completely different and agile form of collaboration between industry and government compared to what has been common practice in Denmark
- Danish companies have their feet held to the fire, but also have their finger on the pulse, as they are the ones who have to invest in both production and consumption
- Establish a clear governance structure where the business sector is continuously involved and consulted about future adjustments to the PtX strategy, and where the government provides ongoing reporting on implementation of the strategy

Figure 21.

Recommended level of ambition and targets for a Danish PtX strategy (2030 and 2050)

	2030 Ambition	2050 Ambition
National climate targets	• **A 70% reduction in annual national emissions compared to 1990** • **Denmark must be a pioneering country and contribute to the green transition and a reduction in carbon emissions outside its borders**	• **Climate neutrality** • **Global contribution to the green transition**
PtX targets		
Consumption	Denmark should reduce CO_2 emissions by 2.5 million tonnes using PtX, allocated as follows: • Heavy road transport: 1-1.5 million tonnes of CO_2 • Aviation: 0.5-1 million tonnes of CO_2 • Shipping: 0.2-0.3 million tonnes of CO_2	• Denmark has an efficient PtX value chain, and hydrogen-based fuels are used in industry, heavy road transport, shipping and aviation
Production	• Denmark has 3+ GW of electrolysis capacity and corresponding RE capacity, in addition to the green electricity required for direct electrification	• Denmark has sufficient RE production and electrolysis capacity to meet domestic needs, and to also export significant quantities of PtX
Exports	• Denmark is a net exporter of PtX fuels and technology, and positioned to serve as a major exporter of renewable hydrogen and hydrogen-based fuels	• Denmark exports significant quantities of renewable hydrogen and renewable hydrogen-based fuels as well as technology and solutions

SOURCE: Danish Energy, Bain & Company analysis.

4.1. PtX ambition in Denmark

Denmark has to use PtX to become climate neutral, and to contribute to the global green transition by exporting energy and technology. The ambition is based on the Danish Climate Act's national reduction targets for 2030 and 2050, as well as the aim that Denmark should be a pioneer country in relation to the green transition and actively contribute to reducing global emissions by exporting green energy, technology and solutions (see Figure 21).

To reach the 70% reduction target by 2030, Denmark needs PtX to decarbonise the sectors of the economy that cannot be decarbonised through direct electrification, energy efficiency improvements or other existing solutions. As a green pioneer, Denmark must also contribute to the transition outside its borders. PtX will thus be a relatively small driver of the emissions reduction towards 2030, but play a much greater role towards full climate neutrality in 2050. It is therefore important that our actions today address both the 2030 target, and lays the foundation for exploiting the climate and economic opportunities that come after 2030.

The target of the Danish PtX strategy should be a reduction of 2.5 million tonnes of CO_2 by 2030

It is recommended that an ambitious Danish PtX strategy should deliver 2.5 million tonnes of CO_2 reductions in the road transport, aviation and shipping sectors. Around 1.5 million tonnes will contribute to reducing national emissions by 2030, and count towards the 70% target[24], while around 1 million tonnes will reduce international emissions from ships and aircraft departing from Denmark.

By comparison, the government has estimated that PtX can deliver 0.5-3.5 million tonnes of CO_2 reductions by 2030 (see Section 2.1).

PtX target is divided into production, consumption and export

To meet the target, PtX production will require around 0.35 million tonnes of hydrogen by 2030, which can be produced with approx. 3 GW of electrolysis capacity[25]. The optimal electrolysis capacity to service the PtX production depends on a number of factors, and could be higher. The ambition is therefore 3+ GW electrolysis.

Denmark is in a good position to export PtX products, technology and knowledge. This will contribute to the green transition outside its borders, and also to scaling up and developing the Danish PtX industry. High demand for renewable hydrogen from northwest Europe is expected as early as 2030[26]. Danish hydrogen production capacity should therefore match the most ambitious forecasts for Danish PtX consumption.

4.2. Ten policy areas to deliver on the ambition

The government's PtX strategy aims to help reduce Danish and global CO_2 emissions and kick-start a new green industry that can create jobs and income for Denmark. Ten policy focus areas aim to translate the goals into action, and support the industrial scaling up of PtX consumption and production in and around Denmark.

Nationally, the Danish authorities must contribute to kick-starting a Danish PtX industry through subsidies and regulation. They must also plan to establish the necessary framework, infrastructure etc. in time to lay the foundation for industrialisation of the market.

1. **Support for value chain projects:** Support for projects for the production of PtX products corresponding to 0.5 GW of electrolysis must be tendered in 2021-2022. Value chain projects

[24] The climate partnership for the energy and utilities sector recommended a 1.9 million tonne reduction by 2030 using PtX, as a contribution to the 70% target. The higher estimate is due to higher displacement from road transport.

[25] Expected electrolysis plants with 6,000 full-load hours per year that produce hydrogen for synthesis plants, as well as electrolysis plants with 4,000 full-load hours, the hydrogen from which is used directly.

[26] Germany, the Netherlands and France are expected to import around 2 million tonnes of hydrogen in 2030.

must link production and consumption, helping PtX transition from test projects to large-scale production and kick-starting a national PtX economy. Projects can either be scaled up in size or number. Production and demand must be developed in step. Project participants must therefore represent a complete PtX value chain that enables industrialisation across sectors.

2. **Production support for PtX:** Production support for renewable hydrogen and other PtX products must be tendered out in the 2023-2026 period, and ensure that a further approx. 2.5 GW of electrolysis is established. Tenders must ensure that PtX production is ready when demand is in place. They should therefore be planned well in advance, based on expected consumption. The Danish authorities must build models that take into account the support needed for the production of PtX fuels, and undergird development of the energy system. By 2030, the need for risk sharing with the public sector will be high.

3. **Carbon capture and utilisation (CCU) for PtX:** Give priority to using green CO_2 for PtX fuels. Create incentives for Danish companies to build plants at Danish point sources of green CO_2, which is necessary to produce green e-kerosene etc. This must therefore be given priority in a national CCU/S strategy. The Danish authorities must therefore support development of the capture and utilisation of green carbon sources in particular.

4. **Tariff and grid connection model:** Update the tariff and grid connection model to better incorporate and support PtX plant and similar plants. Electricity consumers have to pay to use the grid, based on the load and load alleviation they can offer the grid and the energy system in general.

5. **Financing models for conversion of consumption:** Establish supporting funding in addition to government funding to accelerate the green transition on the consumption side. A climate fund will initially be relevant to aviation, but later possibly also to heavy road transport and shipping.

6. **Requirements to replace fossil fuels:** Introduce measures to ensure the transport sector is decarbonised, such as CO_2 displacement and blending requirements, or requirements for green transport in public tenders. The best-suited measures vary across the road transport, aviation and shipping sectors.

7. **Infrastructure:** Plan and develop the necessary infrastructure. The infrastructure must enable the transition to consumption, production and export of renewable hydrogen and hydrogen-based fuels. The Danish authorities must ensure that infrastructure does not become a bottleneck that impedes exploitation of the climate and commercial opportunities PtX entails. The focus area involves actions targeting electricity and hydrogen infrastructure, hydrogen filling stations and ports.

Internationally, the Danish authorities must work for regulation, particularly EU regulation, and international collaboration that promote demand for and trade in PtX products and technology.

8. **PtX certification:** Danish effort to introduce a EU sustainability certification system – and international certification longer term – for renewable hydrogen, green carbon and renewable hydrogen-based fuels. The certification must document green, sustainable fuels, to facilitate cross-border trade in PtX products and increase the value of green fuel to consumers.

9. **EU regulation and framework for PtX:** Danish proactive focus on EU legislation that sets the framework and market rules for PtX in relation to production, consumption and infrastructure. It is important that the EU sets ambitious decarbonisation requirements. This will reduce the risk of relocation for Danish companies that go a long way in the green transition. Denmark must attract as much EU funding as possible, e.g. from the EU recovery package.

10. **International cooperation:** Establish international cooperation, including agreements with other countries to ensure renewable hydrogen and PtX technology is exported/imported. Work must also be done to establish international requirements for the green transition in sectors that operate internationally.

4.3 Economic impact towards 2030 from implementation of the initiatives

Establishment of production capacity capable of supplying hydrogen and hydrogen-based fuels will require significant investments leading up to 2030.

There is also a need for additional investment on the consumption side and the establishment of new infrastructure. We therefore expect a total PtX investment requirement of around DKK 30 billion by 2030.

Table 1
Investments in relevant PtX focus areas towards 2030

Focus area	Investments towards 2030 (DKK billion)
Production plants (value chain projects: 0.5 GW electrolysis)	5-7
Production plants (production support: 2.5 GW electrolysis)	17-23
Consumption conversion	2-3
Infrastructure	1-2
Total	**25-35**

Production plants consist primarily of electrolysis plants for hydrogen production and synthesis plants for further processing PtX products. Production plants for value chain projects require investments of around DKK 5-7 billion, while production support in addition to value chain projects requires around DKK 17-23 billion. Electrolysis and synthesis plants account roughly equally for the total investment during the 2020-2030 period.

Consumption conversion, which covers extra investment in hydrogen trucks, buses and ships, will require up to DKK 2-3 billion. Infrastructure encompasses investment in hydrogen filling stations for heavy road transport, where a total of DKK 1-2 billion in capital investment is needed. Infrastructure for the electricity grid, hydrogen grid and district heating has not been calculated in the analysis. The necessary investments in RE power generation capacity and carbon capture plants have also not been calculated in the analysis.

The private actors who will be making these significant investments need to be sure that there is demand for the new fuels. Compared to fossil fuels, PtX products will not be competitive in the coming years. A number of measures will therefore be needed to encourage demand. These measures are detailed under recommendations in section 5.

The measures described support the possibility of selling hydrogen and hydrogen-based fuels in various ways. Some measures reduce the production cost for the new fuels by subsidising investments and production. Other measures increase the cost of the competing fossil fuels, directly or indirectly, thereby ensuring price parity for the new fuels.

Figure 22 shows the extra costs of more expensive PtX fuels, as absolute amounts and amounts per PtX unit. The total extra cost will increase as more projects are established, while the cost per PtX unit produced is expected to reduce over time.

The total extra private sector costs required to achieve the recommended PtX level in 2030 are estimated at around DKK 12 billion towards 2030 (the grey and green area in Figure 22). Assuming that around DKK 4 billion is covered by payments from the consumption side, mainly in the form of a climate fund for aviation (green area in Figure 22), around DKK 8 billion in funding is expected to be required up to 2030 (the grey area in Figure 22). The transition also entails a loss of revenue for the government towards 2030 of up to DKK 2 billion, resulting from the transition from fossil fuels subject to taxes to green alternatives. Overall, the government must allocate around DKK 10 billion towards 2030 to realise the strategy.

Financing PtX development

Whichever path Denmark chooses to pursue in supporting a future PtX industry, government co-financing will be needed. The recommendations in this proposal add up to over DKK 10 billion during the period up to 2030. When choosing financing mechanisms, it is essential that the competitiveness of Danish businesses is maintained. Traditional financing through a tax on fossil fuels, for example, would lead to a risk of more Danish-produced goods and services, and ultimately companies, moving abroad. There is also a risk of more cross-border trade if the prices of liquid fuels, for example, begin to exceed those in neighbouring countries. Many people are likely to propose carbon tax increases towards 2030 as an option. However, we believe this is neither desirable nor appropriate as a means of solving the PtX paradox and developing a Danish PtX industry. A carbon tax does not directly support the necessary demand for PtX products. A national carbon tax will only affect Danish demand for green solutions.

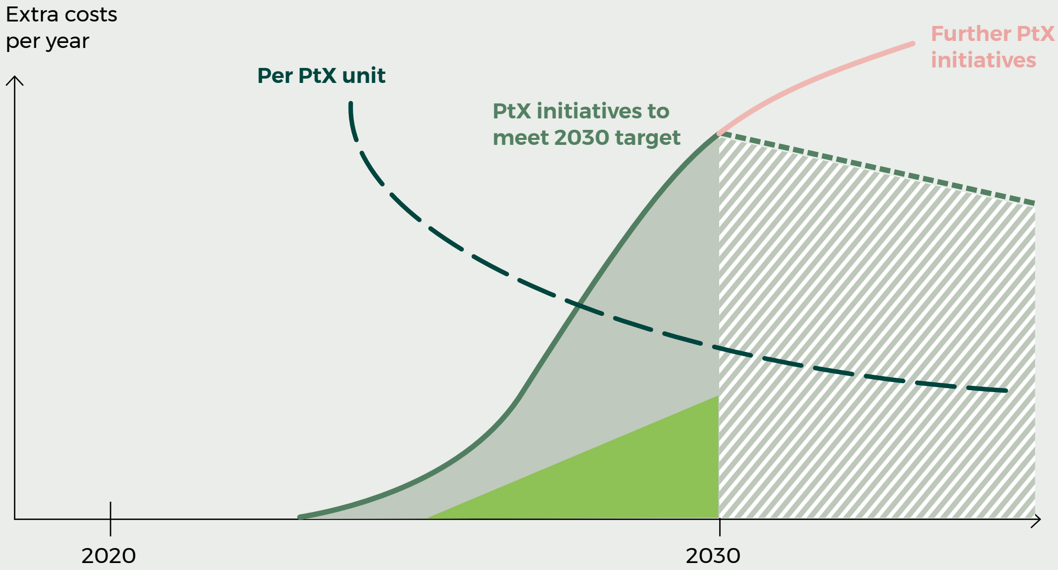
The Danish market is not nearly large enough to support the industrialisation needed to make PtX competitive. A very high carbon tax would also be needed in order to kick-start PtX. The direct impact of this high carbon tax would be increased cross-border trade, whereby consumers refill and bunker outside Denmark. A carbon tax would also have a negative impact on the competitiveness of Danish companies, as they would face a bigger burden than their foreign competitors.

From an industry perspective it would clearly be best if the strategy is financed via the general green funding pool, and reforms that can increase it.

By announcing a green funding pool, the government has shown one way to finance the first phase of the strategy. We recommend that about half of the green funding pool of DKK 2 billion per annum the government has allocated to the climate from 2020 to 2024 be earmarked for the implementation of a PtX strategy, and that funds be reserved for the PtX strategy in the long-term government budgeting.

If the financing from the funding pool is not enough, the government should consult closely with the sectors concerned on how to obtain additional financing. The starting point should be a model whereby the funds collected from a sector's consumers are returned in full to fund the green transition for the given sector. Such mechanisms should only be used to fund the transition for the sector concerned and not as a broad source of funding to achieve the overall 70% reduction target. It is essential in these cases that Danish competitiveness is not impacted, and that the sector really has green alternatives, including the necessary infrastructure. The proposal for Luftfartens Klimafond (the aviation climate fund) is a good example of this, where the climate contribution from passengers is used to cover the higher price of green PtX fuels.
At this stage, this does not appear to be a viable solution for either shipping or heavy road transport, but it is an option that should be borne in mind as green solutions materialise.

Figure 22.
Illustration of the extra costs for PtX up to 2030 and the period thereafter



NOTE: The total extra private sector costs required to achieve the recommended PtX level in 2030 are estimated at around DKK 12 billion towards 2030 (the grey and green area). Assuming that around DKK 4 billion is covered from the consumption side, such as via a climate fund for aviation (green area), around DKK 8 billion in funding is expected to be required up to 2030 (grey area).
SOURCE: Danish Energy.

5.
Recommendations
for policy action

The strategy must lay the foundation for a new green industry that can reduce national and international emissions, while creating jobs and income for Denmark. There is a need for concrete action and initiatives throughout the value chain – from production to consumption.

The sectors are very different in terms of technological PtX maturity and competitive pressure. This affects which measures should be used in each sector. We have therefore split up the recommendations for the sectors into PtX production, heavy road transport, aviation and shipping, as shown in Figure 23. We have combined the broader recommendations into two sections on governance and international initiatives and exports.

Please note that it is a total package, where action needs to be taken and investments made across the entire value chain. No single recommendation can stand alone. A broad range of recommendations is needed to get things started quickly, while also ensuring long-term development.

This is our best plan for how to overcome the PtX paradox and kick-start both production and demand, thereby laying the foundation for a new green industry in Denmark.

Figure 23.
Overview of PtX focus areas and their relevance to consumption, production and export

Governance structure		Focus areas	Consumption			Production	Exports
Governance structure	National	Value chain projects	✓	✓	✓	✓	
	National	Production support				✓	
	National	Carbon capture and utilisation for PtX				✓	
	National	Tariff and grid connection model				✓	
	National	Financing models for consumption conversion		✓			
	National	Requirements to replace fossil fuels	✓	✓	✓		
	National	Infrastructure	✓		✓	✓	✓
	International	PtX certification	✓	✓	✓	✓	✓
	International	EU regulation and framework for PtX	✓	✓	✓	✓	✓
	International	International cooperation	✓	✓	✓	✓	✓

SOURCE: Danish Energy, Bain & Company analysis.

5.1. Governance

To ensure that an ambitious and agile Danish PtX strategy is anchored and executed, it is essential to establish a dynamic organisation to realise the strategy goals. The government invited businesses to participate in addressing the green transition through climate partnerships, and later by establishing the Green Industry Forum. A forum in which involvement of the business sector ensures that decisions and goals are anchored. This is a good first step.

The road to a 70% reduction, and onward towards climate neutrality in 2050, will entail major changes for Danish businesses. Major investments will have to be made, processes restructured and made more efficient, and new products developed and marketed to consumers. Important strategic decisions that need to be made at just the right time in order to maintain and increase competitiveness.

PtX is no exception. The recommendations in this report clearly state what is needed in a Danish PtX strategy to kick-start this area, but also that there are a wide range of factors, such as technological development, commercial opportunities and European and international regulation, that will continually evolve.

Businesses are close to much of this development. It is therefore vital that the business sector is involved, to ensure that Denmark has the best PtX strategy, which will ensure Danish competitiveness in the PtX industry, as well as in the sectors that will be buying the products.

The government must also ensure that it receives regular reporting on the implementation of the ambitions of the strategy, so it can appraise developments and adjust the course and make new decisions if necessary.

A very focused and agile approach will be needed in order to overcome the PtX paradox and guide the very significant investments needed to win Denmark a leading position in building a new PtX industry. Other countries will invest more and have significant industrial infrastructure behind them. If we compete on scale alone, we will lose. But we have a chance if our ability to execute the strategy is better than that of our competitors.

We therefore recommend that a strong governance structure be established around the PtX strategy, which builds on the close cooperation underlying the climate partnerships and the Green Industry Forum, and further strengthens the ties between the business sector and the government. One element of this is that the government appoints a minister responsible for implementation of the strategy and a task force to monitor the strategy and regularly report to the government and the Green Industry Forum on progress and any need for new decisions.

Governance recommendations

Governance	
	A Make a government minister responsible for realising the PtX strategy
	B Establish a PtX task force. Invite key business interests to participate
	C Report on the progress of the strategy's implementation every six months, to allow regular follow-up and adaptation of the PtX strategy

A.

Make a government minister responsible for realising the PtX strategy

To ensure a clear point of contact for businesses and to commit the government to the strategy ambitions, it should appoint a minister as the face and owner of the strategy. Irrespective of the fact that implementing the strategy requires actions that other ministers and ministries have to deliver. The clear assignment of responsibility to ensure progress across ministries should also give businesses a clear point of access to the government and ministries. We know that this can challenge the traditional organisation of work in central government. But this is necessary if we are to beat international competition.

B.

Establish a PtX task force. Invite key business interests to participate

A task force for PtX will be established under the auspices of the Green Industry Forum. Appointed business representatives will regularly monitor development of PtX, and help the government adapt the PtX strategy. The task force will receive secretarial services from the ministry with primary responsibility for implementing the strategy, and business organisations should allocate resources to support the work of the task force, including co-financing it. Officials from other relevant ministries will also be invited to join in the task force's work.

C.

Regularly follow up on and adapt the PtX strategy

Recognising that PtX faces major and as yet unknown changes, regular follow-up and evaluation should be done and the strategy adapted where appropriate. The government and the Folketing must regularly re-visit the strategy and assess whether there is a need to change it.

One of the duties of the task force will therefore be to monitor and report on developments in PtX in Denmark. This includes sending a status report to the Green Industry Forum every six months, and preparing an annual status report that also identifies any need for adjustments to the strategy. The report must be submitted to the government via the minister appointed to have primary responsibility. The government is obligated to review the task force's report in the annual climate programme.

5.2. Production

2020	2030
Electrolysis capacity: 34 MW under construction in Denmark	**Electrolysis capacity:** 3 GW by 2030 · 0.5 GW from value chain projects · 2.5 GW from market supply
RE power: Very little electricity consumption for hydrogen production at present.	**RE power:** 15-20 TWh electricity consumption for PtX purposes, equivalent to say 3-4 GW of offshore wind or 5-10 GW of onshore wind and solar power
Infrastructure: Hydrogen is transported and stored in tanks	**Infrastructure:** A hydrogen grid connects production and consumption units, including any hydrogen storage and pipelines for export

Production of renewable hydrogen
Electrolysis for the production of hydrogen is a well-known technology. Renewable hydrogen production has undergone significant advances in recent years and producers are now ready to move from demonstration to large-scale projects.

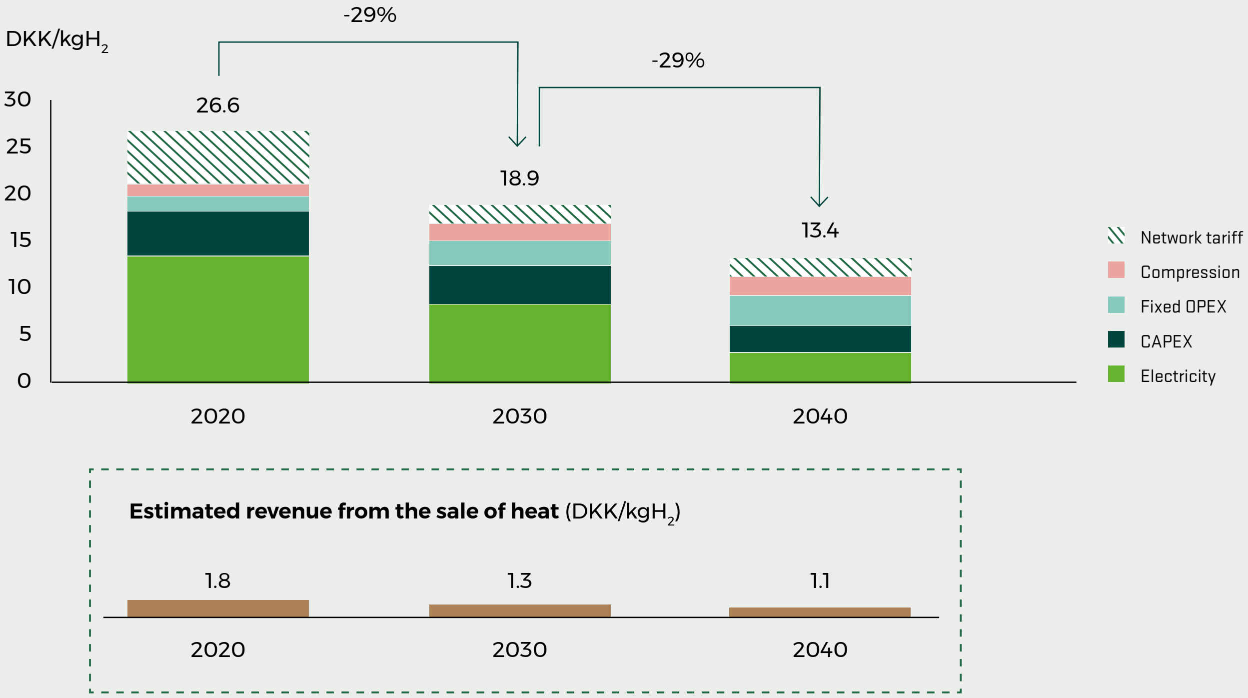
PtX products are currently far from cost-competitive with fossil fuels. Production costs for renewable hydrogen may reduce rapidly, and are expected to decrease by around 20% towards 2030 (see Figure 24). The cost of hydrogen in 2050 is subject to great uncertainty, but several countries have a goal of reducing the price to USD 1/kg. The declining costs towards 2050 will primarily be driven by falling electricity prices and plant costs for electrolysis capacity.

Production of other PtX products
Synthesis plants for the production of PtX products from hydrogen are a well-known and mature technology, but there is still a significant price difference between these PtX products and the fossil alternatives. The falling price of renewable hydrogen will significantly reduce the production costs for PtX products, as hydrogen accounts for up to 75% of these. These costs are expected to fall by around 10-25% towards 2030 for the various PtX products. Despite the drop in costs for both hydrogen and other PtX products towards 2030, there will continue to be a price gap with fossil alternatives.

A number of PtX products, such as e-kerosene and e-methanol, need carbon to achieve the necessary energy density. This should be green carbon from biogenic CO_2, which can be captured when upgrading biogas and from biomass plants. The price of carbon accounts for 10-20% of the total cost, depending on the PtX product.

Collect heat from PtX for district heating
Part of the process loss in electrolysis plants and in some synthesis plants can be used for applications like district heating. Figure 24 shows the estimated income that heat from electrolysis production can contribute to reduce the cost of hydrogen production. The actual value of the heat will depend on factors like the district heating area, the operating hours of the electrolysis plant, the need to increase the temperature for district heating and the certainty of the settlement amount.

Figure 24.
Estimated production costs of renewable hydrogen, DKK per kgH_2



NOTE: The network tariff is shown in 2020 based on the current tariff model (DKK 0.10/kWh), but has been reduced in 2030 and 2040. The heating income is calculated based on 12-15% heat efficiency and a district heating price of around DKK 210-230/MWh.
SOURCE: Ea Energianalyse, Danish Energy, Bain & Company analysis.

Key factors for PtX production and development	Possible ways to handle these factors
Not currently competitive: the price of renewable hydrogen and hydrogen-based fuels is not yet competitive with fossil fuels.	• Production needs to be scaled up substantially and industrialised in order to achieve price parity.
All cost elements and value streams are significant: As the price of electricity falls and efficiency increases, the other price elements will represent an increasing share of the total costs.	• Adjust tariff charges and grid connection so that plants, such as PtX, pays for the load it places on the grid • Electrolysis and synthesis plants generate a lot of heat which can be used for district heating. This sector coupling can help drive down the price of renewable hydrogen if there is certainty of settlement during the depreciation period
Large amounts of green power needed: PtX production needs large quantities of green power. There is a need for 3-4 GW of dedicated offshore wind capacity or 5-10 GW of onshore wind or solar capacity.	• Further expansion in green wind and solar power, possibly linked to offshore energy islands
Variations in location and size: hydrogen can be produced in a range of locations, each with advantages and disadvantages.	• There must be room for all models in the future hydrogen industry. The development of PtX production and infrastructure must keep options open for different solutions, locations and sizes
Lack of hydrogen infrastructure: for production and transport, including distribution abroad.	• Establish hydrogen infrastructure together with and taking into account hydrogen storage and export infrastructure. Analyse whether a hydrogen transmission network can make use of parts of Denmark's existing gas network


H

Recommendations for PtX production

Value chain projects	**A** Support tenders for 2-5 value chain projects with total electrolysis capacity of 0.5 GW, which link production and consumption
Production support	**B** Grant production support for the production of hydrogen and hydrogen-based fuels via tenders to ensure 2.5+ GW of electrolysis capacity is in operation by 2030
Carbon capture and utilisation for PtX	**C** Ensure there is sufficient green CO_2 for use in the production of PtX products
Tariff and grid connection model	**D** Develop tariff and grid connection models so that payment for the grid is consistent with load and load alleviation
Infrastructure	**E** Support hydrogen transport in the short-term with simple Danish regulatory framework legislation which ensures regulatory clarity by 2023
	F Develop and establish a Danish hydrogen grid with connections to neighbouring countries and assess the need for hydrogen storage in the long term

A.

Support tenders for 2-5 value chain projects with total electrolysis capacity of 0.5 GW, which link production and consumption

Kick-start PtX production by tendering 2-5 value chain projects with a total electrolysis capacity of 0.5 GW by 2023. This could be done in rounds as follows:

- Tender round in 2021: In operation by 2025
- Tender round in 2022: In operation by 2026

The need for government production support is estimated at around DKK 3 billion up until 2030. DKK 0.75-1.5 billion in PtX funding[27] from the sale of renewable energy shares to the Netherlands should be used to realise the value chain projects. See a detailed description of the value chain projects on page 48.

B.

Grant production support for the production of hydrogen and hydrogen-based fuels via tenders to ensure 2.5+ GW of electrolysis capacity is in operation by 2030

The tenders must ensure that the production of hydrogen and other PtX products is ready when demand is in place. To achieve the strategy's 2030 ambition, about two thirds of the hydrogen production can be expected to be used for other PtX products. Before commencing tenders, the long-term framework on the demand side and infrastructure should be clarified, so that there is demand for hydrogen and other PtX products at the time production is established.

Certainty of future tenders provides greater security for producers of PtX products and RE power generation, so they can focus on scaling up and development. Hydrogen production corresponding to a total of 2.5 GW electrolysis capacity must therefore be tendered in the 2023-2026 period, and commissioned by 2030. The timing of the tender rounds should be announced as soon as possible.

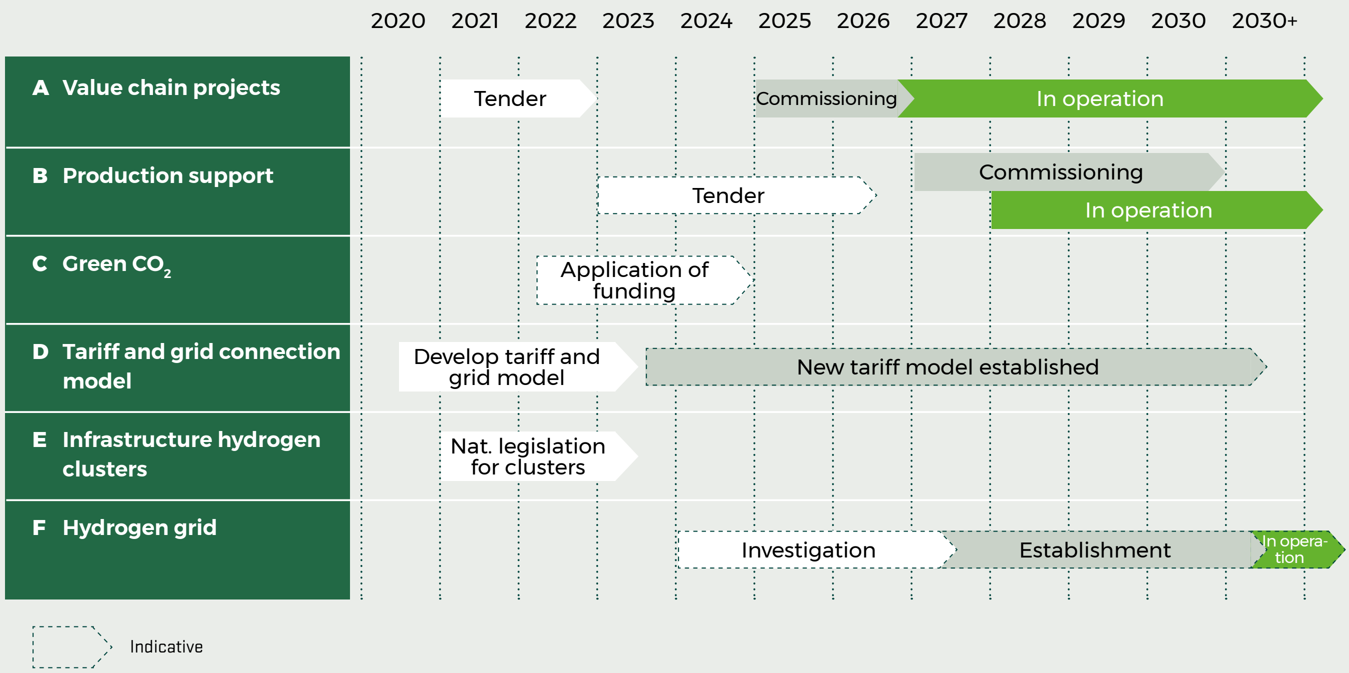
The need for government production support is around DKK 4 billion up to 2030.

C.

Ensure there is sufficient green CO2 for use in the production of PtX products

An ambitious Danish strategy must clearly prioritise the use of green CO_2 for hydrogen-based green fuels. The funding for CCUS in the 22 June 2020 Climate Agreement must be applied to give

[27] The final amount in the agreement with the Netherlands is expected to be known around summer 2021.



investors incentives to invest in and operate carbon capture plants, with a special focus on green carbon point sources. Finally, the need and possibility of transporting CO_2 from point sources for utilisation in the production of PtX products must be examined.

D.

Develop tariff and grid connection models so that payment for the grid is consistent with load and load alleviation

Develop the tariff model in the electricity system so that plants such as electrolysis plants pay to use the grid, based on the load and load alleviation they can offer the grid and the energy system in general. Introduce geographical incentives when connecting to the electricity grid, such as feed zones, which can reward the benefits to the electricity grid resulting from consumption being placed where it reduces the need for expansion. See a detailed description of the tariff and grid connection model on page 50.

E.

Support hydrogen transport in the short-term with simple Danish regulatory framework legislation which ensures regulatory clarity by 2023

Support hydrogen transport in the short term, e.g. point-to-point or clusters established by commercial operators, with simple Danish regulatory framework legislation to ensure regulatory clarity by 2023. This includes developing a model that ensures the transmission and distribution levels are reasonably balanced. See a detailed description of hydrogen infrastructure on page 52.

F.

Develop and establish a Danish hydrogen grid with connections to neighbouring countries and assess the need for hydrogen storage in the long term

Develop and establish a Danish hydrogen grid linked to the transmission grids in neighbouring countries and assess the need for hydrogen storage. This must be done in stages, depending on developments in the volumes nationally and in neighbouring countries and in relevant EU legislation. Investment decisions for the future hydrogen grid must be made with a strong emphasis on contributing to the green transition internationally. See a detailed description of hydrogen infrastructure on page 52.

Use surplus heat from PtX where this is economically viable

PtX has to be able to obtain value for the surplus heat from the production of hydrogen or hydrogen-containing products through agreements to supply commercial heat to heating companies that are not undermined during the depreciation period.

Value chain projects
Deep Dive

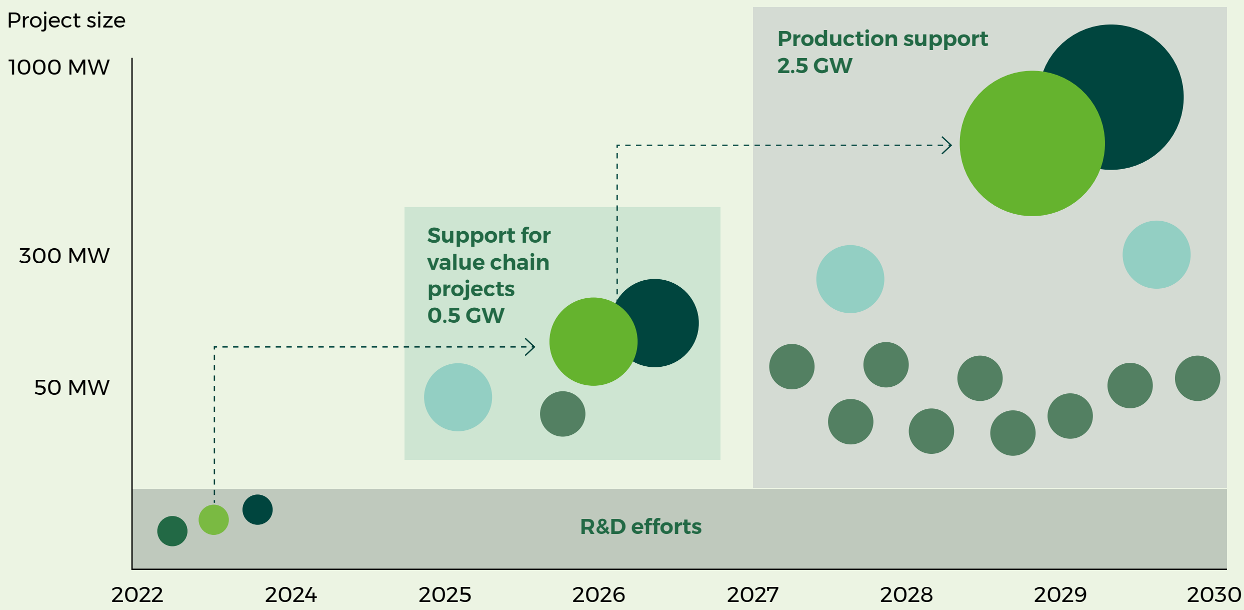
Rationale for value chain projects
The value chain projects must encompass PtX production, infrastructure and consumption – the entire value chain. The projects will kick-start PtX in Denmark by accelerating industrialisation across sectors and demonstrating future solutions on a large scale.

The value chain projects can help address the challenge of structural dependency for PtX in Denmark, i.e. ensure that production and consumption are developed and scaled up in step. Value chain projects can help take PtX from research and development test projects to large-scale demonstration. The value chain projects must ensure that a total of around 0.5 GW of electrolysis capacity is established by 2026. Market tenders for the production of PtX products can subsequently expand production capacity for hydrogen and other PtX products, such that an additional 2.5 GW of electrolysis capacity is constructed by 2030.

Selection criteria for value chain projects
- Project partners must connect a complete PtX value chain, i.e. the project must encompass production and consumption, and possibly new infrastructure.
- The project must be scalable in either size or number. Value chain projects must demonstrate solutions that have high market potential (most likely within heavy road transport, shipping, aviation and export opportunities). Project partners must be able to drive subsequent industrialisation of the value chain.
- The project must show the path to competitiveness for PtX. PtX is one of several green paths to decarbonisation. Projects must therefore have high probability of being among the best and most cost-effective green solutions.
- The project must contribute to development of the energy system of the future, including sector coupling.

Support for value chain projects
Projects should be allocated funding based on a holistic assessment of how they satisfy the selection requirements, and achieving the most PtX production per euro in funding. The selected projects will receive operating funding and possibly construction funding, e.g. to cover infrastructure.

Figure 25.
Illustration of value chain projects and production support



SOURCE: Danish Energy.

Tariff and grid connection model
Deep Dive

Current tariff payment
The tariff payment from electricity consumers must cover Energinet's and the grid companies' costs of operation and depreciation and expansion of the electricity grid. The tariff is divided into transmission and distribution components (see Figure 26) which depend on the point of connection in the electricity grid. The transmission tariff is divided into network and system tariffs. It is currently based on energy consumption and is not allowed to be geographically differentiated. The DSO tariff depends on the network area. The current tariff payment is essentially designed to cover historical costs.

Connecting consumption to the grid happens via one of two models: 1) Consumption is directly connected to the collective electricity grid, where all electricity consumption is subject to tariffs. 2) Consumption connected before the collective electricity grid, where part of the electricity consumption is self-consumption of RE energy. This partially reduces the tariff payment to the collective electricity network.

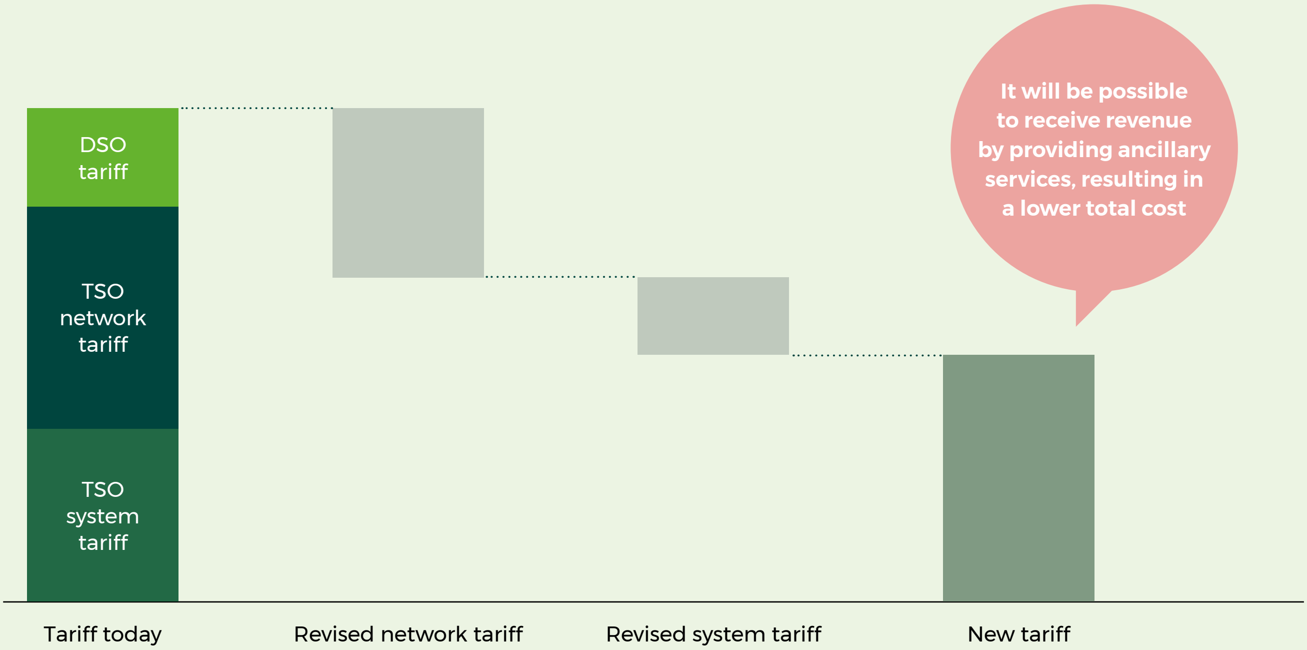
What contribution can electrolysis plants make?
Electrolysis plants can be connected to the power grid in different ways, which will impact how they use and load the grid. The cost to plant owners and society of supplying electrolysis plants depends on a number of factors, such as where the plant is connected to the power grid (voltage level) and whether grid expansion is needed. This depends on the geographical location of the electrolysis plant in the existing power grid, and whether it is interruptible and has guaranteed consumption of RE power.

Electrolysis plants will play a major role in absorbing future RE power generation and can thus help lower the cost of integrating RE into the energy system. Electrolysis plants are expected to have less and less full-load hours in the future as fluctuations in electricity prices increase and the plants become cheaper. Electrolysis plants are expected to be interruptible, and will not consume power during hours with high load and high prices due to price sensitivity. Due to their flexibility in relation to upward and downward regulation, electrolysis plants can provide balancing and thus contribute significantly to the ancillary services market. Different types of electrolysis have different properties and can contribute in different ways.

What changes should be made to tariffs?
Tariff and grid connection models must be developed such that tariff charges for plants such as electrolysis plants reflect the load and load alleviation they can offer the grid and the energy system in general.
Recommended actions:
- allow geographically differentiated consumption tariffs as an incentive for consumption to be located in the electricity grid where it reduces the need for grid expansion. This could be in the form of offshore wind landing zones where electrolysis plants can be placed.
- analyse which payment and connection conditions electrolysis can attain if the plant can be positioned near RE production in the collective grid.
- analyse the possibility of changing the part of the system tariff covering the operation of Energinet, so that it better rewards economies of scale from large electricity consumers, such as electrolysis plants. This might involve switching from a kWh-based payment to a subscription.

Figure 26 illustrates how tariff payments could be lowered from current levels.

Figure 26.
Illustration of components of electricity tariff payment



NOTE: The TSO tariff is based on energy consumption (kWh) and is not geographically differentiated. The tariff consists of:

- a network tariff (around DKK 0.055/kWh). About 50% of this covers network investments (depreciation and interest for the existing power grid) and about 50% covers grid losses, operation and maintenance. Energinet has announced a 'restricted grid access product' which allows interruptible consumers to be exempted from paying for grid investments.
- a system tariff (around DKK 0.045/kWh). About 45% of this covers market payments to ensure security of supply, the majority of which is frequency services. About 55% goes to Energinet's operations, including systems and markets.

The DSO tariff (relevant for electrolysis plants) is currently around DKK 0.02-0.03/kWh (A High) which is paid in addition to the TSO tariff. In the future, this tariff can be expected to become power based. A connection fee is added, which can be reduced through an interruptibility agreement.

SOURCE: Danish Energy.

Hydrogen infrastructure
Deep Dive

Background to hydrogen infrastructure
Hydrogen infrastructure will be used to connect producers and consumers of renewable hydrogen, and is also necessary for exporting hydrogen. Hydrogen production and consumption can be either centralised or decentralised, placing different demands on infrastructure.

Denmark currently has natural gas infrastructure that consists of a transmission network, distribution network and two gas storage facilities. Most of the transmission network is tied to the transport of natural gas until 2038, in existing transport agreements. There are two gas pipelines from Egtved to Germany, one of which could be converted to hydrogen infrastructure. This needs to be evaluated in relation to the future transport of natural gas.

Due to uncertainty about the future production and consumption of PtX products, gradual expansion of the infrastructure with the possibility of continuous adjustment is the best approach. This can start with point-to-point connections and small clusters located where the first production and consumption has to be connected (e.g. in value chain projects).

The construction of new pipelines for hydrogen transport must be coordinated and planned in relation to existing clusters of infrastructure and planned international connections and hydrogen storage. Transmission pipelines can serve as 'transitional storage' via linepack[28] until hydrogen storage is established in one of the gas caverns in the existing gas storage facility or another facility is established. It is also important that the capacity of new infrastructure, such as a hydrogen transmission network and storage, takes into account future hydrogen volumes.

Efficient and competitive exports of Danish hydrogen depend on interconnection with the rest of Europe. Initial plans show this will be possible in 2035. Energinet and the other European gas transmission companies have looked at how a well-interconnected hydrogen grid could be established across north-west Europe (see Figure 27).

An international connection would allow Danish producers to sell hydrogen to foreign companies if Danish consumption is delayed, which would help limit the risk for Danish companies.

[28] Linepack is the 'storage' within the gas grid which allows some time delay between adding and removing gas from the grid.

Figure 27.
Possible interconnected hydrogen network in north-west Europe by 2035

SOURCE: European Hydrogen Backbone Report (by 11 gas transmission operators, including Energinet).

Carbon capture and utilisation for PtX
Deep Dive

Some PtX products, such as e-kerosene and e-methanol, need carbon to achieve the necessary energy density. Carbon should come from green, biogenic CO_2 sources so that the final PtX products are green. It is essential that there is enough green CO_2 to meet the demand for PtX products[29].

There many sources where green carbon can be captured, such as biomass and biogas plants. Figure 28 shows that these carbon sources are expected to provide 5.9 million tonnes of CO_2 by 2030 – enough to meet the need for carbon in PtX products. However, the picture changes between 2040 and 2050, where demand is expected to exceed the available supply of biogenic CO_2. The situation will also be affected if part or all of the green CO_2 is put into long-term storage (carbon capture and storage, CCS). There may be particular interest in storing biogenic CO_2[30], as this counts as negative CO_2 emissions under the UN 'Convention on Climate Change'.

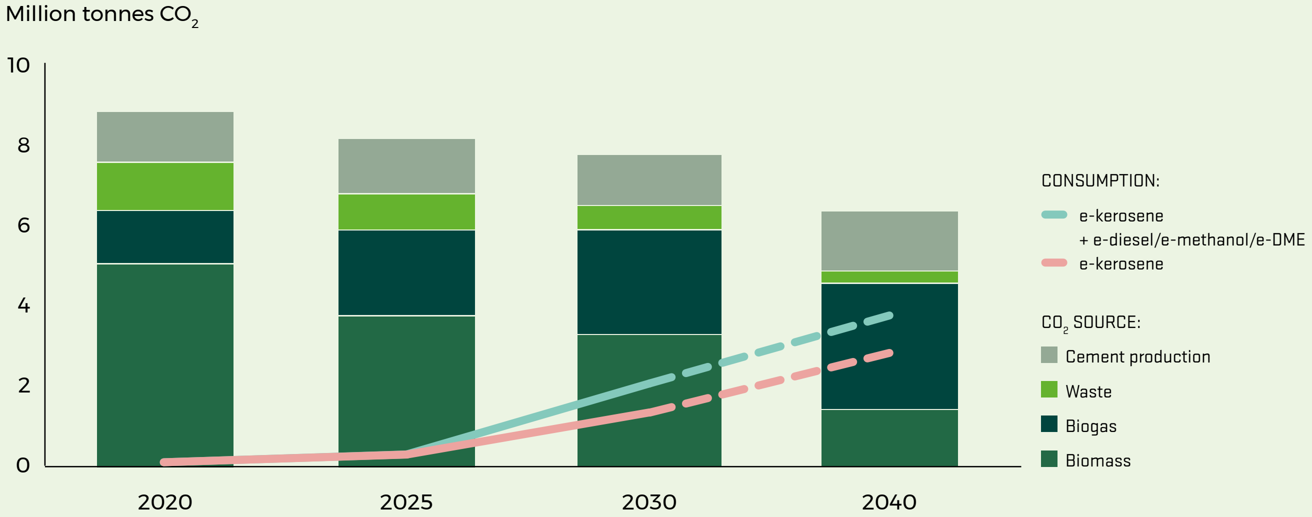
Carbon is currently only captured in Denmark today at Korskro Biogas Plant. The green carbon is then processed and sold for direct use in a number of industries. This accounts for 25% of current Danish CO_2 consumption, and the majority of the remaining CO_2 is imported and based on fossil energy. This existing market for CO_2 for direct use in industrial processes serves as a possible recipient if the capture of green CO_2 exceeds the current demand.

There must be sufficient amounts of green CO_2 to produce future PtX products. This must be ensured through ambitious strategies for CCU and CCS which take into account the PtX strategy, as well as focused application of the allocated funding for carbon capture at green point sources.

It is important that the CO_2 used is green. This needs to be facilitated by an EU certification system for green carbon that ensures documentation and traceability. This will help to set the value of green CO_2 and is a prerequisite for establishing a European commodity market for CO_2 that ensures cross-border trade and efficient pricing based on supply and demand.

[29] The CO_2 greenhouse gas consists of carbon and oxygen. Green, climate-neutral carbon comes from biogenic CO_2 from biological materials, such as wood, straw and organic food waste, which contain CO_2 absorbed from the atmosphere during their life cycle.
[30] Bio energy carbon capture and storage (BECCS).

Figure 28.
Availability and demand for green CO_2



NOTE: Consumption of kerosene has been calculated based on Copenhagen's goal of reducing fuel emissions, and being climate neutral by 2050.
SOURCE: Danish Energy Agency's biomass analysis, Danish Waste Association report on CO_2-neutral waste energy 2030, Nordic Energy Research, Copenhagen Airport, Danish Energy, Bain & Company analysis.

5.3. Heavy-duty vehicles

2020	2030
There are around 42,000 heavy-duty trucks of more than 3.5 tonnes	Goal of around 6,700 hydrogen trucks, or about 15% of the existing fleet
Heavy-duty vehicles have CO_2 emissions of approximately 1.7 million tonnes	A CO_2 reduction of 1-1.5 million tonnes by increasing the use of PtX across the road transport sector
Hydrogen trucks are expected to seriously enter the market from 2023-24	A nationwide network of hydrogen filling stations for heavy-duty vehicles
There are currently 6 hydrogen filling stations for light passenger transport	

Using PtX products to advance the green transition
Conversion of road transport is a process that takes time. Therefore, a framework and goals are needed to kick-start the process and ensure the deployment of hydrogen trucks and the necessary infrastructure.

Heavy-duty vehicles will be able to reduce emissions in the future by using several types of PtX products to varying degrees. Hydrogen trucks[31] and buses are emission-free and relevant across the entire market, but particularly on long-haul routes, as electric trucks are expected to primarily be relevant on short routes.

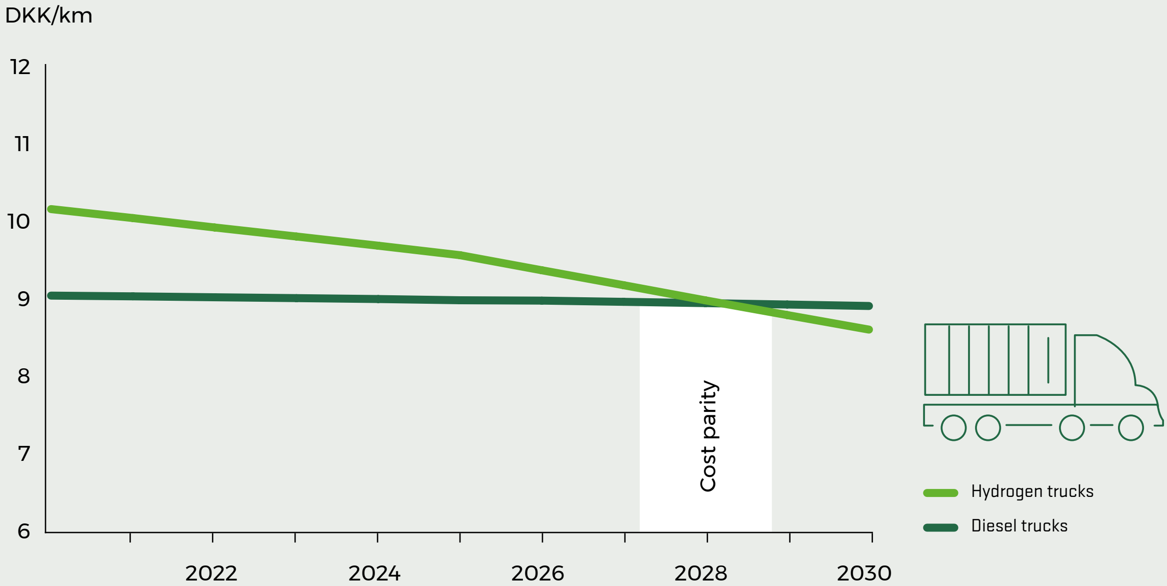
Hydrogen trucks are expected to seriously enter the market around 2023-24, and be competitive with diesel trucks from around 2028 under the right conditions. The drop in the total cost of ownership for hydrogen trucks will be driven by lower hydrogen prices, lower maintenance costs and lower purchase prices for the trucks. With subsidies on the purchase of hydrogen trucks, it would be possible to make them competitive as early as around 2024 (see Figure 29).

However, adequate infrastructure will ultimately be essential in order for the above to fall into place.

Hydrogen-based fuels, such as e-DME and e-methanol, may also help decarbonise heavy-duty vehicles, but these are expected to primarily be relevant for blending during a transition phase.

[31] Fuel cell electric vehicles (FCEV): Hydrogen trucks are fuel cell vehicles that are fuelled by pure hydrogen.

Figure 29.
Total cost of ownership for diesel and hydrogen trucks



NOTE: The total costs have been calculated for trucks that drive 62,500 km per year. Trucks that drive further will have a lower total cost of ownership, and trucks that drive a shorter distance will have a higher one.
SOURCE: Danish Energy, Bain & Company analysis.

Key factors for PtX demand and development	Possible ways to handle these factors
Competition: The market for goods transport is characterised by strong competition and small market shares, both nationally and internationally	• Limit special national requirements that will tend to push the industry abroad or can be circumvented (e.g. by refuelling outside Denmark)
Limited willingness among transport company's customers to pay for green solutions	• Reduce the price gap by making green solutions cheaper • Increase demand through regulation • Ensure that hauliers' costs do not have a double impact, through rising vehicle prices and the cost of new infrastructure
Great uncertainty about technology development and high investment costs deter transport operators from investing in green solutions	• There is a need for a clear framework and financial incentives for choosing green solutions
Infrastructure: There is no hydrogen filling infrastructure for heavy transport that allows trucks to refuel across Denmark and Europe	• Monitor what is happening abroad while building the filling infrastructure, since much of the transport is cross-border. Focus on our neighbouring countries, especially Germany, given that much heavy road transport heads south[32]

[32] Germany is now a leader in rolling out hydrogen filling stations and extensive expansion is underway, with government support. They expect to open station number 100 by the end of 2020. Expansion is expected to continue at a rate of about 15 stations per year thereafter, according to the German Federal Ministry of Transport and Digital Infrastructure.

Recommendations for heavy-duty vehicles

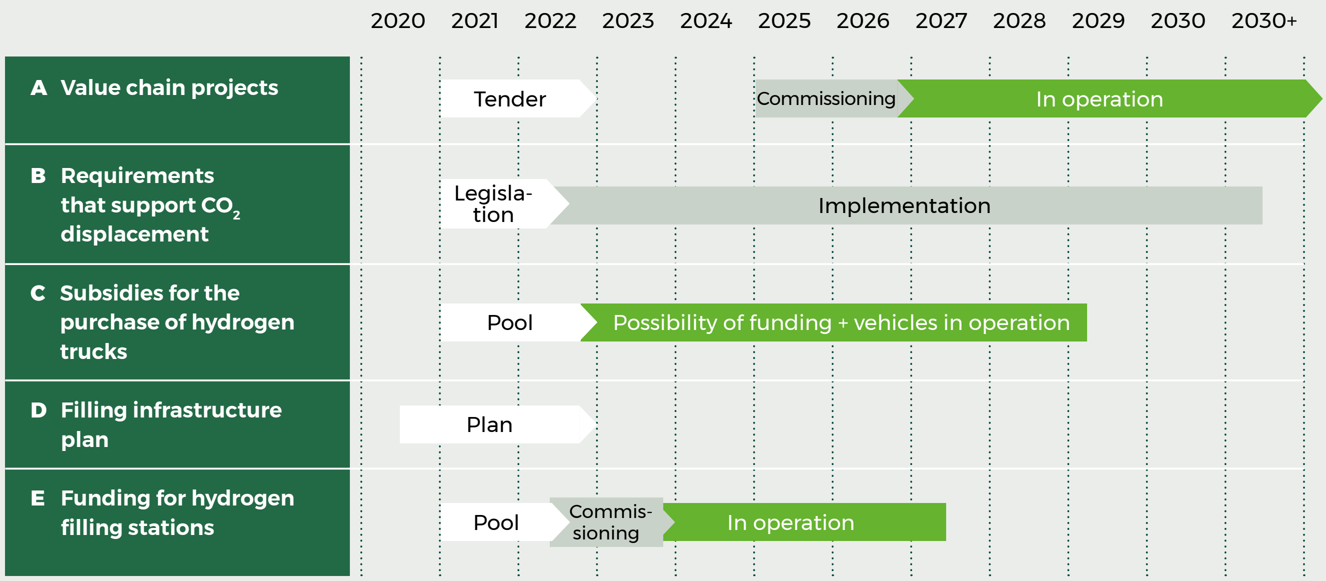
Value chain projects	**A** Tender value chain projects that link production and consumption
Requirements to replace fossil fuels	**B** Introduce requirements that support CO_2 displacement and ensure greater use of PtX for road transport
Financing models for consumption conversion	**C** CAPEX subsidies for the purchase of hydrogen trucks before 2030
Infrastructure	**D** Plan for the expansion of hydrogen filling stations for heavy transport
	E Establish a funding pool for the development of a nationwide network of around 10 hydrogen filling stations to service heavy-duty vehicles

A.
Tender value chain projects that link production and consumption
Value chain projects to kick-start PtX in Denmark must encompass consumption, so that production and consumption are commercially developed and scaled up in parallel. The consumption side could be demand for PtX products for heavy-duty vehicles. The value chain projects must be tendered in 2021 and 2022, with commissioning in 2025 and 2026 respectively, as described in section 5.2.1.

B.
Introduce requirements that support CO_2 displacement and also ensure greater use of PtX for road transport
Introduce requirements to ensure CO_2 displacement in road transport. The requirements must promote increased consumption of hydrogen and other PtX products. An ambitious solution must have a genuine climate effect, and create incentives to utilise the most effective solutions in the green transition, such as PtX products. To avoid creating special Danish requirements that could undermine Danish competition conditions, the Danish Government should work towards ambitious EU legislation that lays the groundwork for a full green transition in the transport sector, and is not just a means towards short-term reductions.

C.
Establish CAPEX subsidies for the purchase of hydrogen trucks before 2030
Subsidies on the purchase of hydrogen trucks must cover the extra cost of purchasing hydrogen trucks over fossil vehicles. This will significantly reduce the extra cost of purchasing a hydrogen truck, and is necessary in order to kick-start the transition. Under the right conditions, the total cost of ownership for hydrogen trucks will be on par with fossil trucks as early as 2027-28. The purchase cost will be higher, but operating costs are expected to be lower. It is therefore essential that financial support is given to ensure that the transition gets underway.

D.
Plan for the expansion of hydrogen filling stations for heavy-duty vehicles
A plan for rolling out public hydrogen filling stations for heavy transport must take into account the expected future needs in Denmark, and the expansion



plans in our neighbouring countries. It is essential that a network of hydrogen filling stations be rolled out before the first hydrogen trucks arrive in Denmark, as no one will invest in the trucks without the necessary filling infrastructure.

Establishing a hydrogen filling station, with planning, permits and construction, takes 18-24 months. It is therefore essential to get started now. Since the heavy transport sector operates extensively across borders, the expansion of the Danish hydrogen infrastructure should monitor Germany's expansion plans as a minimum.

E.

Establish a funding pool for the development of a nationwide network of around 10 hydrogen filling stations to service heavy-duty vehicles

Establish a funding pool for the development of a nationwide network of around 10 hydrogen filling stations to service heavy-duty vehicles. The filling stations must be located at established transport junctions, and the 10 stations will be the first phase in the development of a broader network.

5.4. Aviation

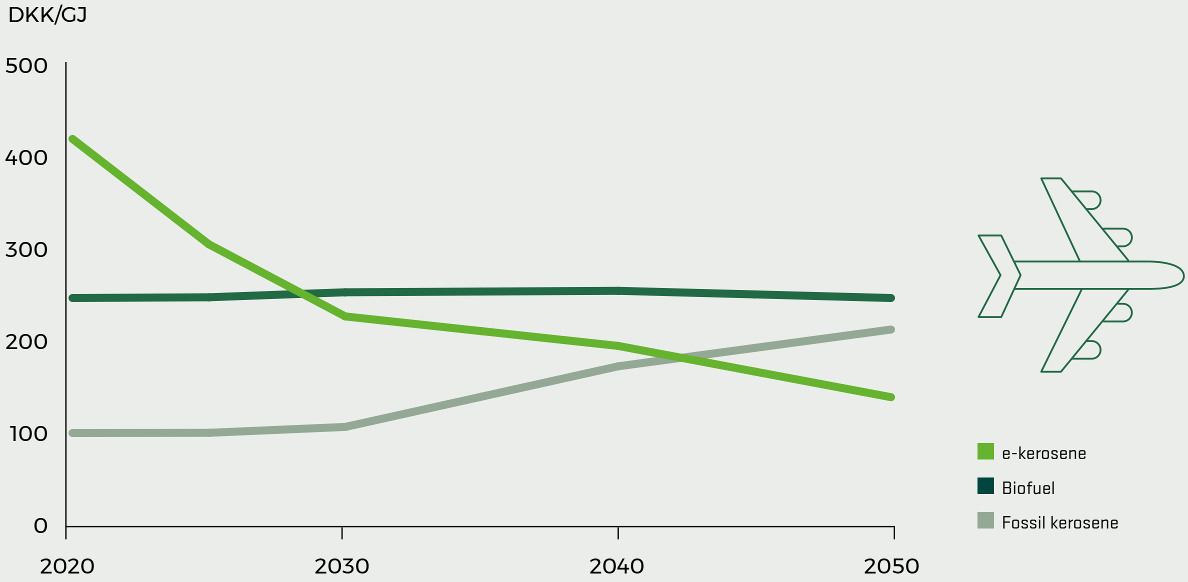
2020	2030
• Danish aviation[33] loads around 44 PJ of aviation fuel per year[34]	• Up to 30% of the fuel used in Danish aviation has been replaced by green fuels, primarily e-kerosene
• CO_2 emissions are around 3.1 million tonnes/year[35]	• CO_2 emissions from Danish aviation have been reduced by 0.5-1 million tonnes/year

Using PtX fuels to advance the green transition
E-kerosene is the only type of sustainable aviation fuel known today that has the potential to be scaled to meet the sector's global consumption in 2050, and which can be used directly in existing engine technologies. There is therefore broad consensus in the aviation industry that e-kerosene is the most relevant alternative to fossil fuels. Aircraft manufacturers are also developing and testing hydrogen aircraft, which may become an alternative in the longer term.

Sustainable aviation fuel is currently far from competitive with fossil fuels. Intensive industrialisation is therefore needed to achieve price parity. The price of green e-kerosene is currently about four times higher than the price of fossil fuel (see Figure 30). The price of e-kerosene is expected to be on par with the price of fossil aviation fuel by 2040-2045, but extensive action will be required to close the price gap. The trend will be largely driven by lower hydrogen prices, as the hydrogen price accounts for about 60% of the cost of producing e-kerosene.

[33] Danish aviation encompasses domestic flights and outbound international flights from Denmark.
[34] Based on data for Jet Petroleum 1 (JP1) from the Danish Energy Agency's energy statistics for 2018. JP1 is a petroleum grade used for aviation that is subject to strict requirements for low levels of water and unsaturated compounds.
[35] Sector roadmap for the Aviation Climate Partnership.

Figure 30.
Expected price trends for various types of aviation fuel



NOTE: There are major uncertainties associated with the price of e-kerosene. This analysis shows a high and low estimate for the e-kerosene price. Carbon emission allowances are expected to increase the price of fossil kerosene after 2030.
SOURCE: Hydrogen Council, Danish Energy, Bain & Company analysis.

Key factors for PtX demand and development	Possible ways to handle these factors
Competition: The aviation sector is highly competitive internationally. Aircraft normally have to refuel on landing, and can therefore only circumvent regulatory intervention on fuel to a limited extent, but care must be taken not to regulate Danish aviation and airports too harshly, as this could lead to refuelling at foreign airports (carbon leakage) and/or fewer stopovers and long-haul routes from Danish airports	• Minimise special national requirements that will tend to push the industry abroad or can be circumvented (e.g. by refuelling outside Denmark) and/or supplement with supporting measures • Denmark must work towards European or international solutions to promote transition in the aviation sector
Willingness to pay: There are signs of some willingness to pay among consumers and airlines, but it remains limited. Funding is therefore needed to drive the green transition, as long as green fuel remains significantly more expensive than fossil fuels	• Introduce the Aviation Climate Fund as a funding mechanism. This will encourage significant demand for sustainable aircraft fuels despite a high price differential. • Reduce the price gap by making green solutions cheaper and/or black solutions more expensive
Certification of approved aviation fuels is a slow process, and only one type of e-kerosene is currently approved for up to 50% blending. Uncertainty about the success and timing of approval is a key barrier to investment in the production of other types of PtX-based fuels which could potentially be produced more cheaply and with higher energy efficiency than the current approved type	• Joint action within the EU is necessary to gain approval of new PtX-based fuel types and blending in excess of 50% and streamline approval processes

Recommendations for aviation

Value chain projects	**A** Tender value chain projects that link production and consumption
Financing models for consumption conversion	**B** Establish a climate fund based on climate contributions from passengers
Requirements to replace fossil fuels	**C** Introduce blending requirements to support the advance of PtX-based aviation fuels
EU regulation and framework for PtX	**D** Work towards joint EU action for international approval of all relevant types of PtX-based aviation fuels
	E Work to introduce EU regulation to replace national initiatives
International cooperation	**F** Work towards global regulation

A.

Tender value chain projects that link production and consumption

Value chain projects to kick-start PtX in Denmark must encompass consumption, so that production and consumption are commercially developed and scaled up in parallel. The consumption side could be demand for PtX fuels for aviation, which could help establish a supply chain for sustainable aviation fuel. The value chain projects must be tendered in 2021 and 2022, with commissioning in 2025 and 2026 respectively, as described in section 5.2.1.

B.

Establish a climate fund based on climate contributions from passengers

In the absence of effective European and global regulation, Denmark should establish the climate fund proposed by the Aviation Climate Partnership, involving climate contributions from passengers departing from Danish airports by 2021. A legal framework would have to be put in place. The climate fund must be managed by an independent board, which sets the climate contribution and recommends the required blending level. The fund will ensure demand for sustainable fuel and support investment in competitive PtX production. It is essential that national, fiscal taxation on air travel is not introduced.

C.

Introduce blending requirements to support the advance of PtX-based aviation fuels

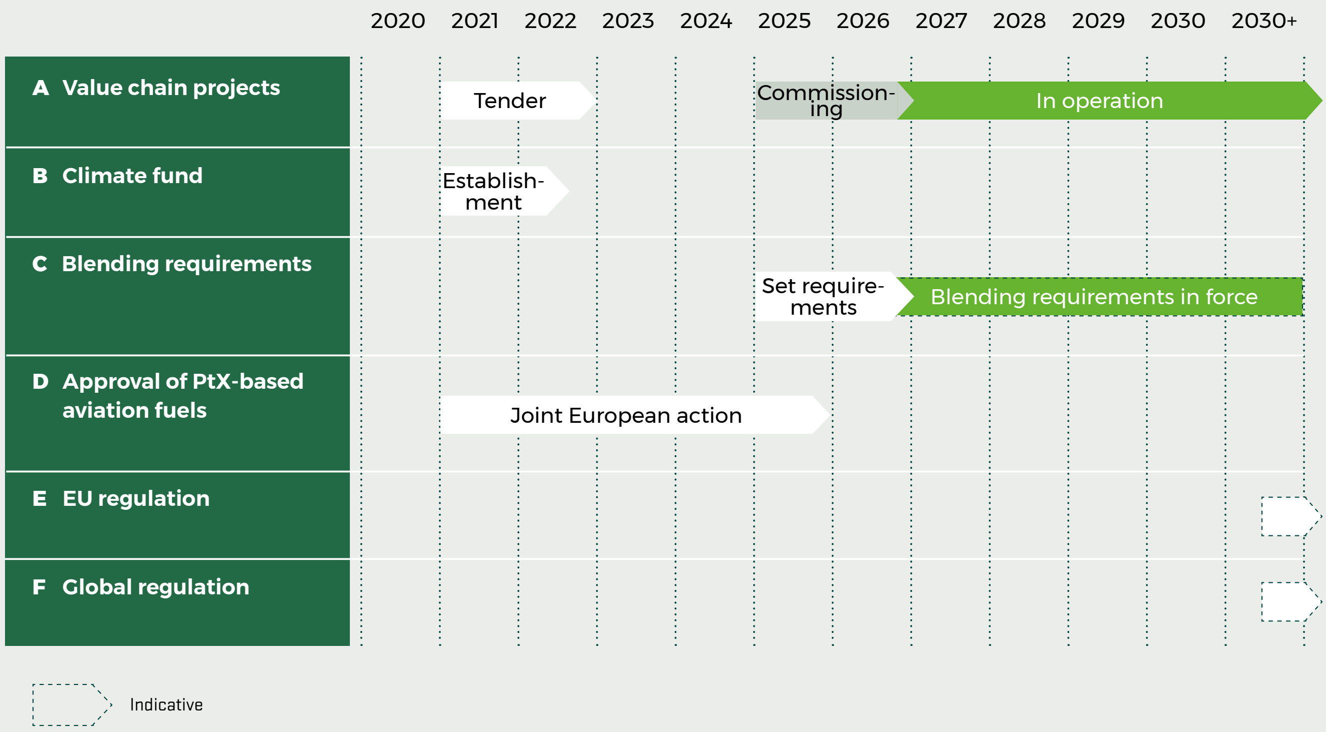
Introduce a blending requirement to support the adoption of PtX-based aviation fuels, in order to reach the sector's 30% reduction target by 2030[36]. The blending requirement is set regularly by the Minister of Transport, based on the recommendation of the board of the Aviation Climate Fund.

D.

Work towards joint EU action for international approval of all relevant types of PtX-based aviation fuels

It is important that all relevant types of PtX-based aviation fuels are approved for use, so that airlines can choose the cheapest available PtX-based aviation

[36] Reduction target for 2030 set in the sector roadmap for the Aviation Climate Partnership.



fuel. Denmark and the EU must therefore push for approval from ASTM (American Standard for Testing and Materials), which approves which fuels can be used in aviation.

After 2030, it needs to be possible to blend in more than the 50% green fuel that ASTM currently permits. The EU should work together in a coordinated manner to ensure that this is approved as soon as possible.

E.

Work to introduce EU regulation to replace national initiatives

Abolition of the tax exemption on jet fuel in the EU Energy Taxation Directive could enable EU taxes on fossil fuels to replace various national aviation taxes, and contributions to the climate fund. This will would put all flights and refuelling within the EU on an equal footing. If the EU introduces a tax on fossil aviation fuel, aviation should be decoupled from the ETS. It is assumed that EU revenue from the taxes will be returned to fund the green transition for the aviation industry, including the production of PtX-based aviation fuel. Similarly, it would be good to replace national blending requirements with an EU requirement.

F.

Work towards global regulation

Denmark must work towards eventually replacing national and European regulation with a global emission-based carbon tax, directly dependent on carbon emissions. Administration of this tax should be simple and efficient, and the proceeds must be returned to support the transition of the aviation sector to the use of sustainable fuel. This will be the best mechanism for achieving the highest possible global CO_2 reduction, without adversely affecting the competitiveness of Danish companies. However, it will take time to implement, so other measures are needed to kick-start the transition before then.

5.5. Shipping

2020

- Around 0.8 million tonnes of CO_2 are emitted in Danish territorial waters, divided equally between ferries, fishing vessels and other boats
- Ferries to Norway and Sweden emit around 0.2 million tonnes per year on 10 routes
- Danish shipowners emit around 53 million tonnes of CO_2 in international waters

2030

- CO_2 emissions in Danish territorial waters and for ferry services to neighbouring countries reduced by 0.1-0.2 million tonnes CO_2/year due to the use of PtX fuels
- CO_2 emissions from shipping near Denmark can be reduced by 0.1-0.2 million tonnes CO_2/year by converting 5-10 small container ships that sail fixed routes in the North Sea and Baltic Sea

Using PtX fuels to advance the green transition
There are several technological options for the green transition in shipping. Pure electricity solutions are expected to be used for shorter routes. In the long term, e-methanol and e-ammonia are expected to be the dominant green fuels. Some ships are already powered by methanol, while the first ammonia-powered ship is expected to be ready in 2024. E-ammonia and e-methanol can therefore be used as fuel in shipping (if the ships are modified) but are not expected to be available on a large scale before 2030.

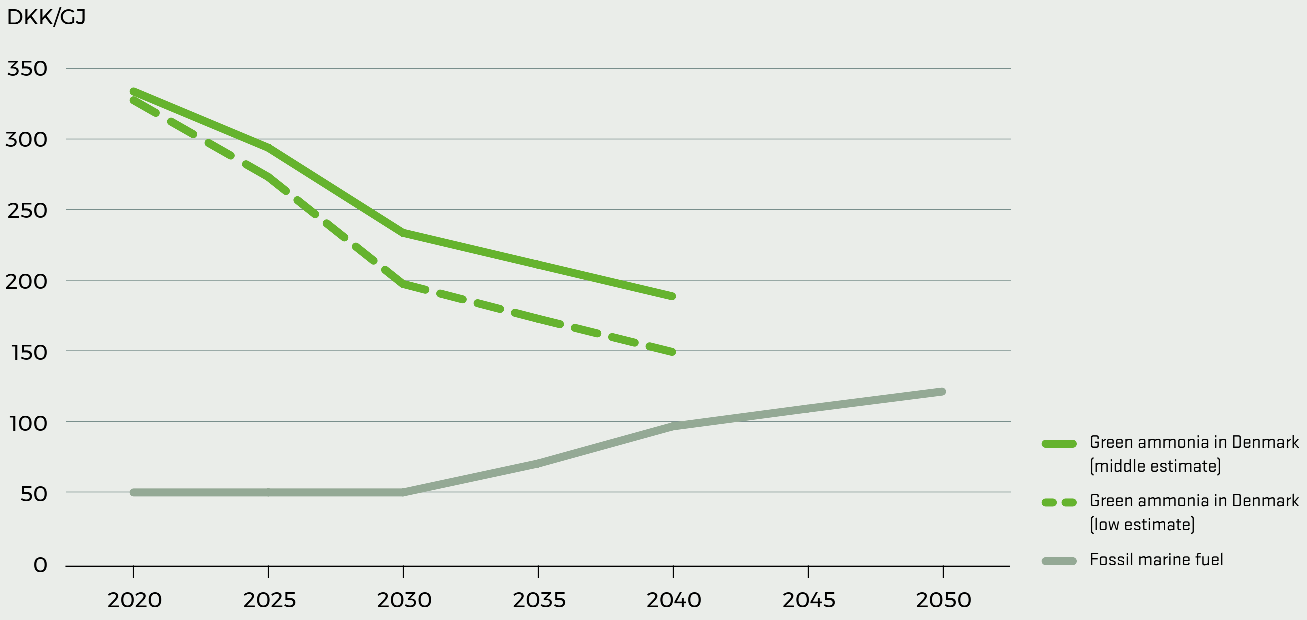
The total costs for a container ship powered by e-ammonia are currently four to five times higher than for ships using traditional fossil fuels. Around 90% of the total cost is tied to the price of renewable hydrogen for the production of e-ammonia, while the capital cost of the ship's drivetrain accounts for about 10%. Declines in the price of green ammonia and a potentially higher carbon tax on fossil fuel are likely to reduce the price gap in the future (see Figure 31).

The market for e-ammonia in shipping is expected to only take off globally after 2030, when the price gap between green and fossil marine fuel has reduced, and new ships and infrastructure can be ready. The transition requires major investments in ships and infrastructure, which have a long depreciation period (25-30 years). This means that the green transition in shipping is expected to be relatively slow. There is expected to be a mix of different sustainable and fossil fuels for an extended period.

Using PtX for ferries can lead to CO_2 reductions and provide experience for upscaling
Electric and hydrogen ferries[37] may be relevant for short routes, for example to Danish islands. Long-distance ferry services, e.g. from Denmark to Norway and Sweden, will be relevant for testing fuels such as methanol, as engines have already been developed that can be used. Ferries that operate short and medium routes are ideal for testing, and then scaling up for merchant and fishing vessels.

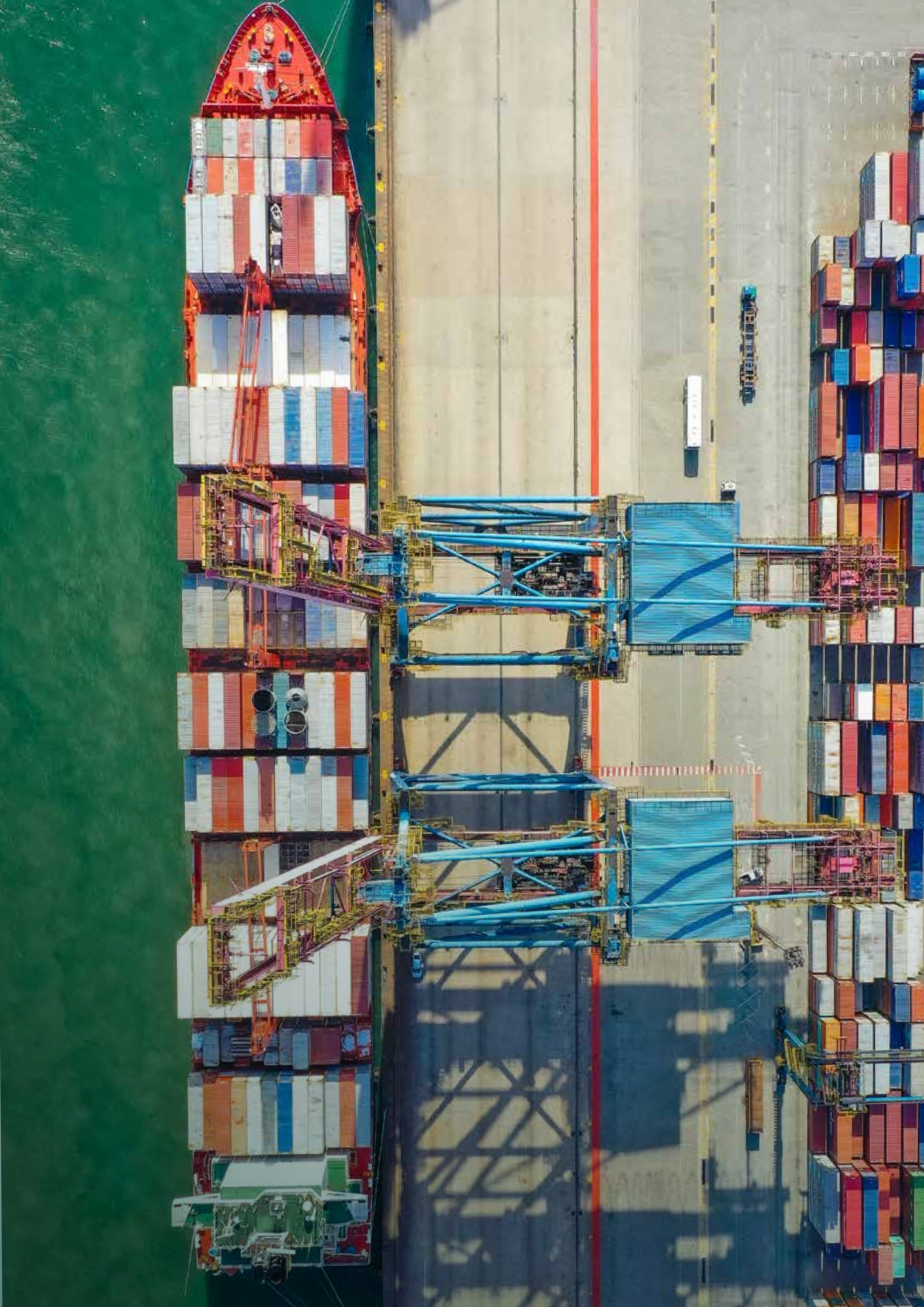
[37] Hydrogen ferries will be electric ferries with fuel cells to extend their range and are technologically comparable to heavy Fuel Cell Electric Vehicles (FCEVs). The choice between batteries and hydrogen depends on factors like the route distance, time between departures and cost of electricity infrastructure.

Figure 31.
Price expectations for green ammonia[1] and fossil marine fuel[2]



NOTE: [1] Production price for green ammonia in Denmark based on Danish electricity prices (source: Ea Energianalyse).
Global price levels for green ammonia are estimated at around DKK 220-290/GJ in 2025, DKK 140-210/GJ in 2030 and DKK 90-150/GJ in 2040-2050 (source: Topsøe et al, "Ammonfuel – an industrial view of ammonia as marine fuel", 2020).
[2] Fossil marine fuel for the 2020-2030 period has been set at USD 300/MT (median price for years 2016-2020). From 2030-2050, a carbon emissions allowance payment of around DKK 1,000/tonne in 2050 has been added.
SOURCE: Danish Energy, Ea Energy analysis.

Key factors for PtX demand and development	Possible ways to handle these factors
Lack of technological maturity: Ships powered by PtX fuels are still under development. Ship engines powered by fuels such as ammonia are still under development, as is fuel handling	• Testing of PtX fuels in new ship engines may be carried out on converted ships initially
International competitiveness: International shipping is characterised by intense competition between shipping companies. Special Danish legislation can therefore distort competition and harm Danish competitiveness	• Minimise special national requirements that will tend to push the industry abroad or can be circumvented (e.g. by refuelling outside Denmark) and/or supplement with supporting measures • Push for international legislation to raise CO_2 reduction requirements from shipping
Low willingness to pay: There is generally a low willingness to pay among customers. Only a small segment (<1%) is willing to pay an extra 10% for sustainable transport, which is equivalent to paying 30% extra for green fuel. There is a rising number of customers who are focusing on their carbon footprint throughout the value chain	• Reduce the price gap by making green solutions cheaper and/or black solutions more expensive • Increase demand through regulation • Collaborate with customers seeking green transport solutions
Lack of infrastructure and regulation: No Danish ports currently have the necessary infrastructure, and major investment will be needed for conversion. There is a lack of guidelines covering the use of new fuels, such as permission for refuelling while unloading and loading the ship	• Enact the necessary legislation to make it possible to refuel ships using new PtX fuels in ports in Denmark and the EU



Recommendations for shipping

Value chain projects	**A** Tender value chain projects that link production and consumption
Requirements to replace fossil fuels	**B** Ensure national ferry services are green
Infrastructure	**C** Develop a green port strategy
EU regulation and framework for PtX	**D** Work towards PtX-ready port infrastructure in the EU
	E Lobby the EU and IMO[38] to raise the 2030 targets
International cooperation	**F** Establish a Scandinavian partnership to advance fossil-free ferry services
	G Create a regional partnership to advance fossil-free shipping in the Baltic Sea and North Sea regions

A.

Tender value chain projects that link production and consumption

Value chain projects to kick-start PtX in Denmark must encompass consumption, so that production and consumption are commercially developed and scaled up in parallel. The consumption side could be demand for PtX fuels for shipping. This could be created by establishing green national ferry routes and kick-starting PtX for regional shipping and ferry services. The value chain projects must be tendered in 2021 and 2022, with commissioning in 2025 and 2026 respectively, as described in section 5.2.1.

B.

Ensure national ferry services are green

Municipalities must ensure there is a reasonable transition to green ferry services. This can be done when tendering out ferry services or by placing other requirements on the routes. As a minimum, targets for 2025 and 2030 should be set. The analysis of options for green conversion of Danish ferry routes agreed in 'Aftale om udmøntning af pulje til grøn transport' (agreement on establishing a fund for green transportation) from April 2020 could serve as a basis. This analysis is expected to be complete in November 2020.

C.

Develop a green port strategy

Initiate the process for an ambitious new port strategy, aimed at securing infrastructure for refuelling using methanol and/or ammonia, particularly in strategically important ports. The strategy must identify the need for changes to regulations that make it possible to refuel using new fuels, and possibly set emission requirements for ships in ports, etc. It is essential that the competitiveness of Danish companies is not adversely impacted, and this must be taken into account when formulating a green port strategy.

D.

Work towards PtX-ready port infrastructure in the EU

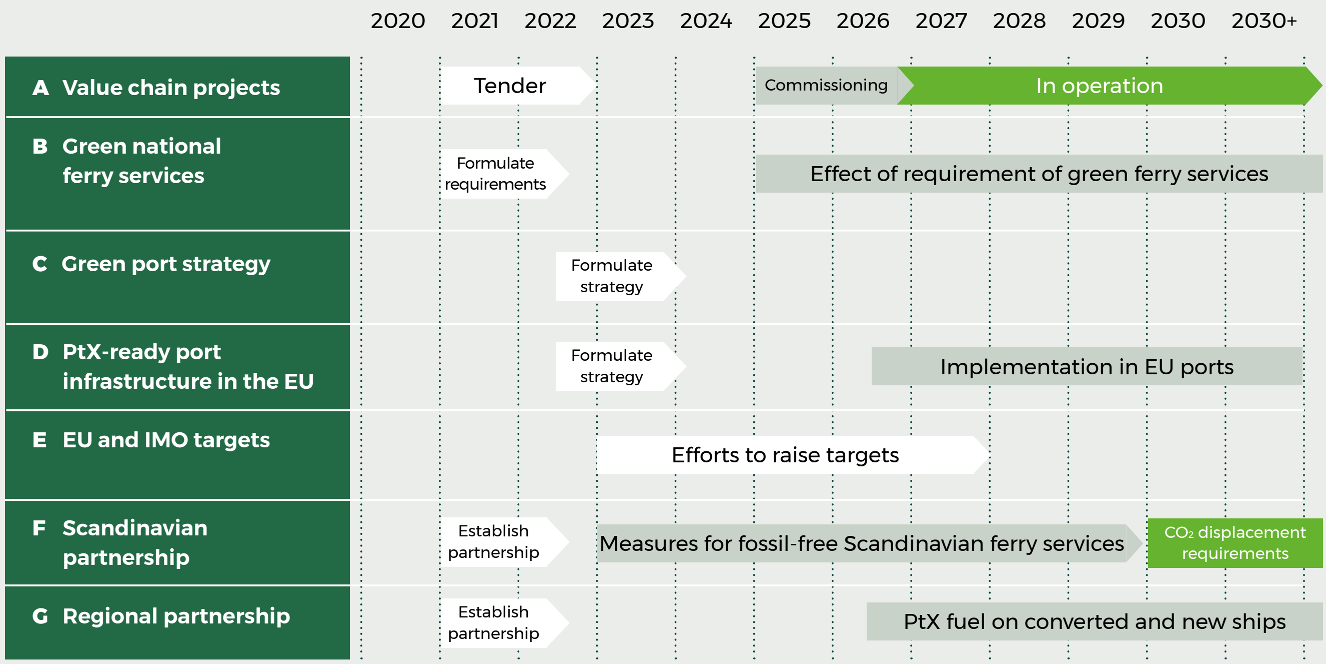
The EU should designate port infrastructure as a key area that can advance the green transition for shipping, particularly in relation to PtX. It is important that the EU takes the lead, to ensure there is a level playing field between ports in the Member States. In addition to ensuring functional refuelling options in ports, guidelines for refuelling using new fuels are also important, so that container ships can be refuelled while loading/unloading, etc.

E.

Lobby the EU and IMO to raise the 2030 targets

The current target for 2030 of a 40% CO_2 reduction

[38] IMO: The International Maritime Organisation is an organisation under the United Nations that coordinates international shipping conditions, including setting requirements.



requirement per tonne of freight needs to be increased. Taxes on fossil fuels must also be increased. There is a need for ambitious climate regulation within the IMO, which can be implemented and enforced uniformly for all ships globally, so that there is no competition distortion. Denmark should play an even more active role in the IMO.

F.
Establish a Scandinavian partnership to advance fossil-free ferry services

Establish a regional Scandinavian partnership that includes a technology-neutral 30% CO_2 displacement requirement by 2030 for fuel used for regional ferry services within and departing from Denmark.

Ferry services between Denmark, Sweden and Norway have an annual fossil fuel consumption of about 3 PJ. Ferry services from Hirtshals and Frederikshavn account for about 2 PJ of this. Ferry routes between countries are often longer and thus difficult to operate using batteries or hydrogen. Therefore, green fuels like e-methanol can be a solution.

G.
Create a regional partnership to advance fossil-free shipping in the Baltic Sea and North Sea regions

Establish a regional partnership for fossil-free shipping, e.g. in the Baltic Sea and/or North Sea region, where countries actively hedge risk and provide funding to build infrastructure and establish fossil-free regional shipping routes. The funding must cover investment in conversion or new vessels, necessary infrastructure and operating subsidies for PtX fuels.

One example of fossil-free shipping collaboration could be the gradual conversion of feeder ships (small container ships) that operate regular services between a number of ports in the North Sea and Baltic Sea region. Feeder ships, which currently use 5-7,000 tonnes of fuel per year, can be converted or new vessels purchased which use methanol or ammonia. 1-2 ports with infrastructure will be needed to service the feeder ships. In Denmark, this could be Aarhus Harbour. In around 2025-2027, existing feeder ships and port infrastructure could be converted to support green PtX shipping in the region.

The Baltic Sea region is a good place to start demonstration projects, as ships have set routes in the area and there are environmental requirements stipulating more expensive low-sulphur fuels. Denmark can provide a framework for collaboration, such as financing the production of green fuels and regulating shipping operations.

5.6. International action and export

2020	2030

• A central pillar of the climate act from 2020 is that Denmark must be a pioneering country and contribute to the green transition and a reduction in carbon emissions outside its borders
• This should be achieved by exporting:
  • green energy in the form of renewable hydrogen
  • technology, solutions and knowledge
	• Denmark is a net exporter of PtX products, technology and services in 2030
	• Definitions and certification systems for renewable hydrogen, green CO_2 and PtX products are in place

International action and export of PtX products and technology
Denmark is in a good position to export renewable hydrogen, due to its extensive wind resources and good geographical location, which allows exports via the North Sea, etc. It is important that there are low transport costs, as this will offer a competitive advantage over renewable hydrogen from cheap solar energy in North Africa and the Middle East. Exporting renewable hydrogen, PtX technology and know-how will help Denmark to quickly attain an industrial scale, which is necessary to reduce costs.

Denmark has many companies that develop and deliver technology, solutions and knowledge to much of the PtX value chain. Exporting this technology and knowledge of commercial solutions, may help advance the development of these companies. This contributes to the green transition outside Denmark, and will help establish a significant Danish PtX industry.

It is vital to Denmark's leading position that it be actively involved in the European and international collaborations and organisations focusing on PtX and the green transition in general. In the European context, Denmark should take on an active role in the hydrogen alliance and join IPCEI[39] in order to give Danish companies the best possible conditions.

As part of the EU's industry strategy, the European Commission has established the Clean Hydrogen Alliance, which aims to ensure an ambitious implementation of hydrogen technologies in manufacturing, industry and transport. As part of the Green Industry Forum, the Danish Government has already joined the hydrogen alliance. One of the most tangible tools from the hydrogen alliance is the IPCEI possibility for hydrogen. IPCEI allows the Danish government to provide funding to hydrogen projects in excess of what existing state aid rules allow. If Denmark joins IPCEI, it could give Danish companies better conditions and increase the possibility of participation in strategic large-scale projects across European borders.

[39] IPCEI: Important Project of Common European Interest.

Key factors for international action and exports	Possible ways to handle these factors
International competition: A number of countries in North Africa and the Middle East expect to see large-scale production of hydrogen and PtX fuels using cheap solar energy	• Measures to reduce production and transport costs
European competition: A number of European countries have formulated hydrogen strategies and allocated significant funds for development of hydrogen production and the hydrogen industry. Several countries have also concluded collaboration agreements for the import and export of hydrogen[40]	• International partnership agreements, especially with our neighbouring countries
Infrastructure: Efficient and competitive export of Danish hydrogen will depend on the establishment of hydrogen infrastructure to connect Denmark to the rest of Europe	• Initial studies by gas transmission operators show that a north-west Europe hydrogen grid may be possible by 2035 • No EU regulation for hydrogen infrastructure yet exists, but is underway
European and international demand: EU regulations and international organisations such as the IMO already set a number of mixing or displacement requirements, but the level of ambition needs to be raised	• European and international green transition targets need to be raised • These requirements will increase demand and create a level playing field that does not impair Danish competitiveness
Cross-border trade in renewable hydrogen, green carbon and renewable hydrogen-based fuels: Renewable hydrogen will be a key energy carrier in the future. The potential for Danish hydrogen production can only really be exploited when there is production, consumption and trade within the EU. Hydrogen is not currently regulated the same way as electricity or natural gas	• Certificates for renewable hydrogen, green carbon and renewable hydrogen-based fuels will be necessary to demonstrate that energy is sustainable and emission-free. They will also be important for trade • EU regulation: Market rules and a framework are needed to ensure access to infrastructure (when it is in place)

[40] In summer 2020, the Netherlands and Portugal signed a memorandum of understanding/collaboration agreement on the development of a strategic value chain to secure production of renewable hydrogen in Portugal, for export to the Netherlands via ships to the Port of Rotterdam. The agreement also covers knowledge sharing and collaborative research in relation to hydrogen. Germany and Australia have signed an agreement to explore ways of creating a value chain together. The goal of the agreement is to study the best ways to share knowledge on production, technology, storage and transport. Germany is also holding discussions with France on joint hydrogen projects in the GW class, with the aim of making the two countries leaders in hydrogen in Europe.

Recommendations for international action and export

Infrastructure	**A** Establish a Danish hydrogen grid with a connection to Germany and participate in coordinating a interconnected hydrogen transmission grid
PtX certification	**B** Push for rapid and ambitious definitions for sustainable and climate-neutral hydrogen and green CO_2 in the EU
	C Pressure the EU on certification of renewable hydrogen, green CO_2 and renewable hydrogen-based fuels
EU regulation and framework for PtX	**D** Proactively influence EU legislation that sets the framework and market rules for PtX
	E Work for ambitious and rising EU CO_2 emissions reduction targets
International cooperation	**F** Proactively work towards international collaboration agreements with other north-west European countries
	G Take advantage of EU funds and opportunities in IPCEI

A.

Establish a Danish hydrogen grid with a connection to Germany and participate in coordinating a interconnected hydrogen transmission grid

A well-interconnected hydrogen grid between Denmark and our neighbouring countries must take into account future hydrogen volumes and the need and options for storing hydrogen. This must be built in cooperation with neighbouring countries. See a detailed description of hydrogen infrastructure in section 5.2.3.

B.

Push for rapid and ambitious definitions for sustainable and climate-neutral hydrogen and CO_2 in the EU

Definitions that stipulate what is green and sustainable are a prerequisite for establishing certification systems. See a detailed description of definitions for renewable hydrogen and CO_2 in section 5.2.4.

C.

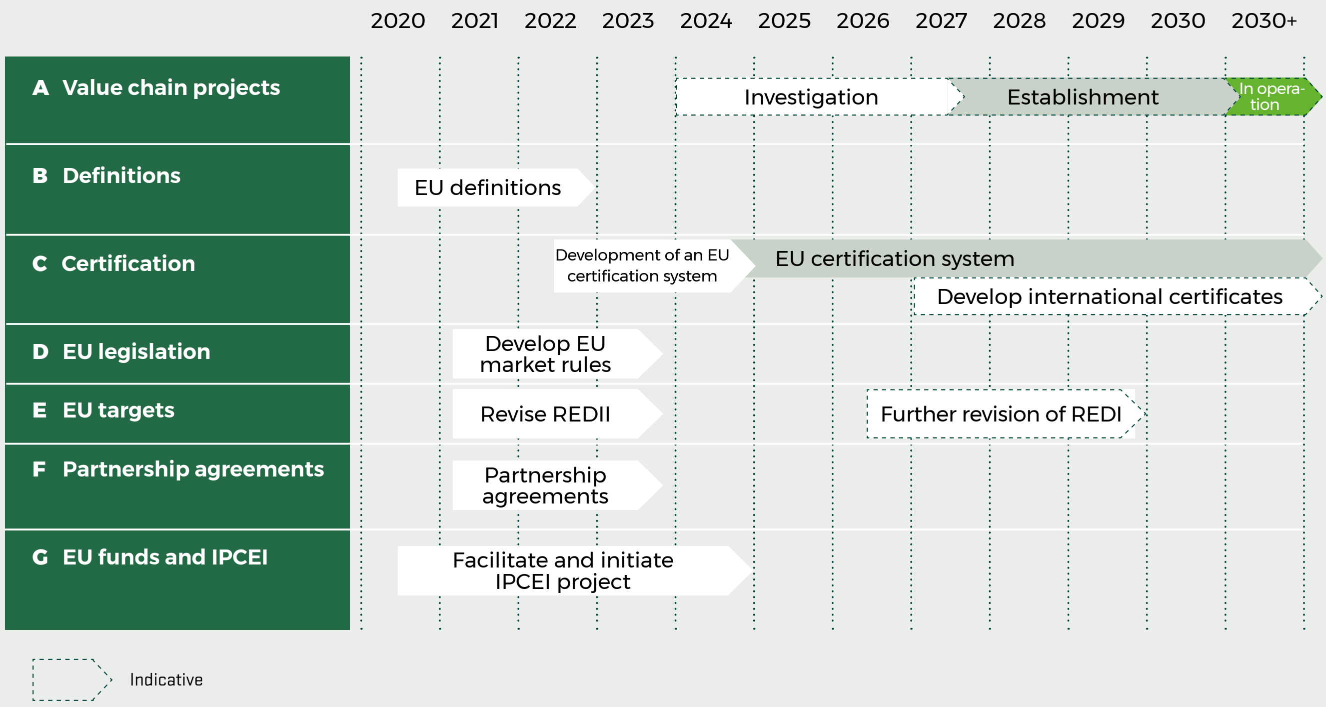
Pressure the EU on certification of renewable hydrogen, green CO_2 and renewable hydrogen-based fuels

Certification systems are necessary to document green energy and green fuels for the demand side, and must also support trade in PtX fuels. See a detailed description of certification systems in section 5.6.1.

D.

Proactively influence EU legislation that sets the framework and market rules for PtX

Proactively influence EU legislation to provide fair and transparent regulation of hydrogen infrastructure, including regulating access to and tariffing of transmission networks and hydrogen storage. There must also be fair, transparent and simple regulation of an internal hydrogen market in the EU.



E.

Work for ambitious and rising EU CO_2 emissions reduction targets

The EU's requirement for the general share of renewable energy in European energy consumption needs to be more ambitious than the current 32% level in the REDII[41]. The requirements for the use of renewable energy in specific sectors need to be significantly raised. This is especially true for the transport sector (land transport, aviation and shipping), which is currently set at 14% in REDII. The EU is working on a revised REDII. The revision should increase the sectoral target for shares of renewable energy in transport and ensure further strengthening of the target over time.

Finally, the EU must actively pursue CO_2 reduction targets in the global transport sector, so that Danish and European companies in sectors like aviation and shipping can make the transition, without adversely affecting their global competitiveness.

F.

Proactively work towards international collaboration agreements with other north-west European countries

Work should be done to establish collaboration agreements with European countries, such as Germany and the Netherlands. The aims of the agreements should include influencing the framework and legislation for PtX in the EU, coordinating PtX strategies and plans, and concluding relevant cross-border agreements on imports and exports.

G.

Take advantage of EU funds and opportunities in IPCEI

Denmark must apply for and use the EU funds available for PtX projects and developing a PtX industry to the full extent possible, including the EU recovery package, in which hydrogen is identified as a key sector. Denmark must also attempt to receive a share of the EU funding available for research and development in hydrogen and PtX.

[41] REDII: Directive 2018/2001 of 11 December 2018 on advancing the use of energy from renewable sources.

Certification system
Deep Dive

Background to certification system
Certificates can document the sustainability of renewable hydrogen, green carbon and renewable hydrogen-based fuels, providing certainty and documentation for the companies that consume them. Certificates also enable and support national and cross-border trade in these energy carriers and fuels, between producers and consumers, which can highlight and increase value.

When establishing a certificate system, it must be decided whether there will be a physical delivery and connection, or a more virtual system without a direct link between the certificate and physical delivery.

Denmark must work towards a market for green PtX fuels in the EU by promoting PtX certification. This will involve definitions and classification of the energy sources and fuels covered, based on a life cycle assessment of climate impacts and sustainability. The certificates must be recognised by all EU countries.

Certification system recommendations – elaboration
A.
Push for rapid and ambitious definitions for sustainable and renewable hydrogen and carbon in the EU
By the end of 2021, the European Commission has to adopt a delegated act to complement REDII, which sets forth detailed rules for when hydrogen based on renewable electricity generation for use in the transport sector can be defined as renewable. To this end, the EU rules on CO_2 levels in electricity used for the production of renewable hydrogen need to be clarified, which allow power purchase agreements (PPAs) to be included in the definition of renewable hydrogen for the transport sector.

The EU hydrogen strategy also needs to be rapidly and ambitiously implemented. The strategy defines different types of hydrogen, as well as 'hydrogen-based synthetic fuels'. These definitions must apply to all applications.

The European Commission is planning a revision of REDII, to be adopted in the first half of 2021, which will reflect higher climate goals and the EU's strategies for hydrogen and the integration of energy systems and sector coupling.

Biogenic CO_2 is generally considered to be green, but this is not stipulated in the EU legislation, which is necessary in order to establish certificates for CO_2. This should therefore be defined in the coming revision of REDII.

B.
Pressure the EU on certification of renewable hydrogen, green CO_2 and renewable hydrogen-based fuels
Introducing certification systems for renewable hydrogen, green CO_2 and renewable hydrogen-based fuels, which are recognised across EU countries, will promote trade in these green energy sources and fuels and the creation of an internal market. An international certification system would also be relevant for renewable hydrogen-based fuels that are used and potentially traded internationally. This will reduce the documentation burden and ease trading for companies that operate internationally.

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DANSK ENERGI

DANISH ENERGY
VODROFFSVEJ 59
1900 FREDERIKSBERG

+45 35 300 400
WWW.DANSKENERGI.DK
DE@DANSKENERGI.DK

FACEBOOK.COM/DANSKENERGI
LINKEDIN.COM/COMPANY/DANSK-ENERGI
TWITTER.COM/DANSKENERGI