WHEN TRUST MATTERS

Techno-Economic Analysis of a Danish Hydrogen Infrastructure

Part 1 of 3: Energy system modelling for hydrogen production and offtake

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Introduction

Background

The Danish gas grid and economy can be decarbonized with hydrogen and multi-quality gasses. Hydrogen production and offtake, also with export scenarios, have to be connected with pipelines. The existing pipelines can be retrofitted, or new dedicated can be constructed. The symbiosis of the Energinet TSO grid, and the Evida DSO grid, will play a crucial role to both decarbonized domestic use, and export hydrogen to Germany, or transmit hydrogen from the North Sea, Norway and Sweden to Europe.

There is a need to assess the emerging production and offtake with scenarios on when, where and how the production will come, and where the need is the greatest. The gas grid can be modelled and optimized based on the production and offtake scenarios. A socio-economic perspective is needed to understand the total cost-benefit for the Danish society.

Part 1 of 3: Energy system modelling for hydrogen production and offtake

DNV has modelled the development of the Danish Hydrogen economy by assessing the supply of hydrogen from renewable sources and demand from end-users to decarbonise across sectors. DNV has developed three scenarios covering a low, medium, and high uptake of hydrogen decarbonisation across the demand sectors based on three development areas for hydrogen:

- Export – target export of renewable green hydrogen to demand outside of Denmark
- Decarbonisation – Usage of hydrogen to decarbonise sectors, will consider alternative technologies
- Replacement – direct replacement of current industries using grey hydrogen (refineries, ammonia production)

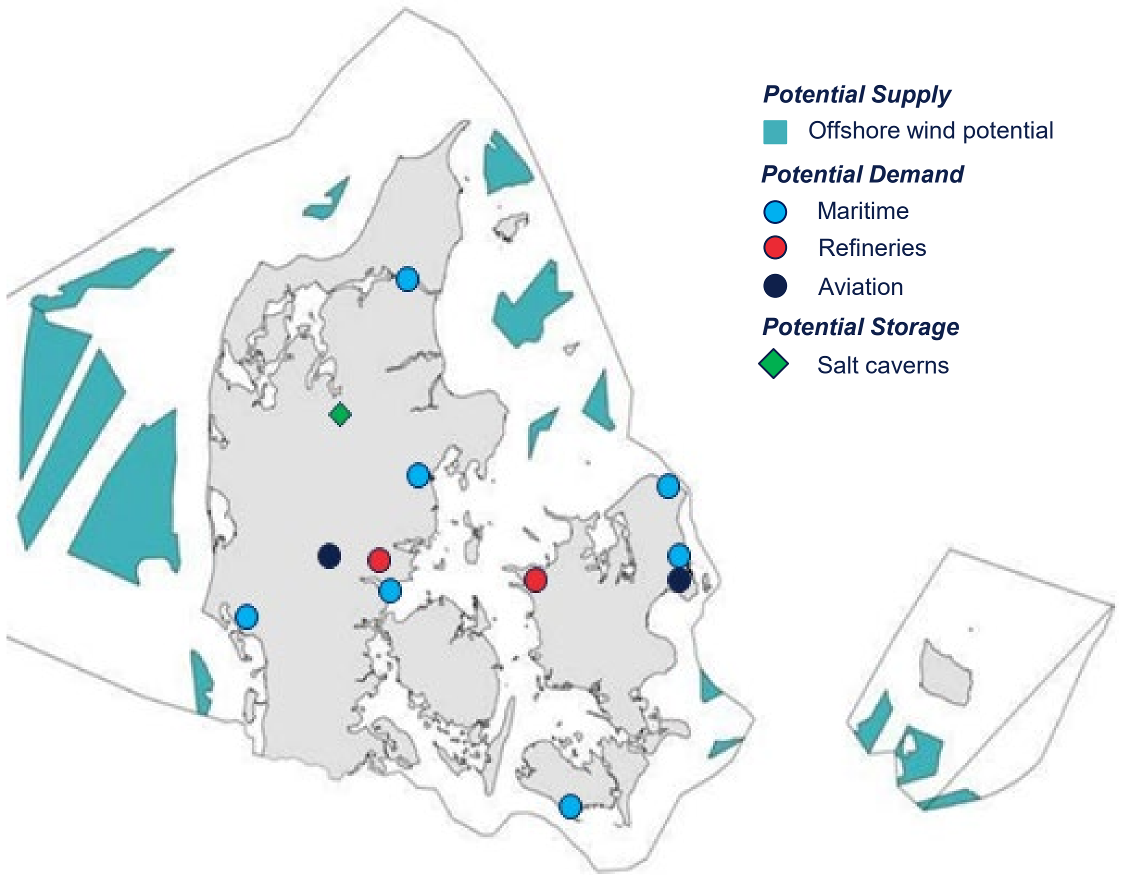
Evida with the support of DNV have undertaken an initial high level assessment of this need to stimulate discussion and raise awareness of potential demand pathways and decisions required in the short term to support long term development plans and growth in the Danish hydrogen economy.

This report is a part of a wider study commissioned by Evida finalised in April 2022 and updated in July 2022.

The Opportunity

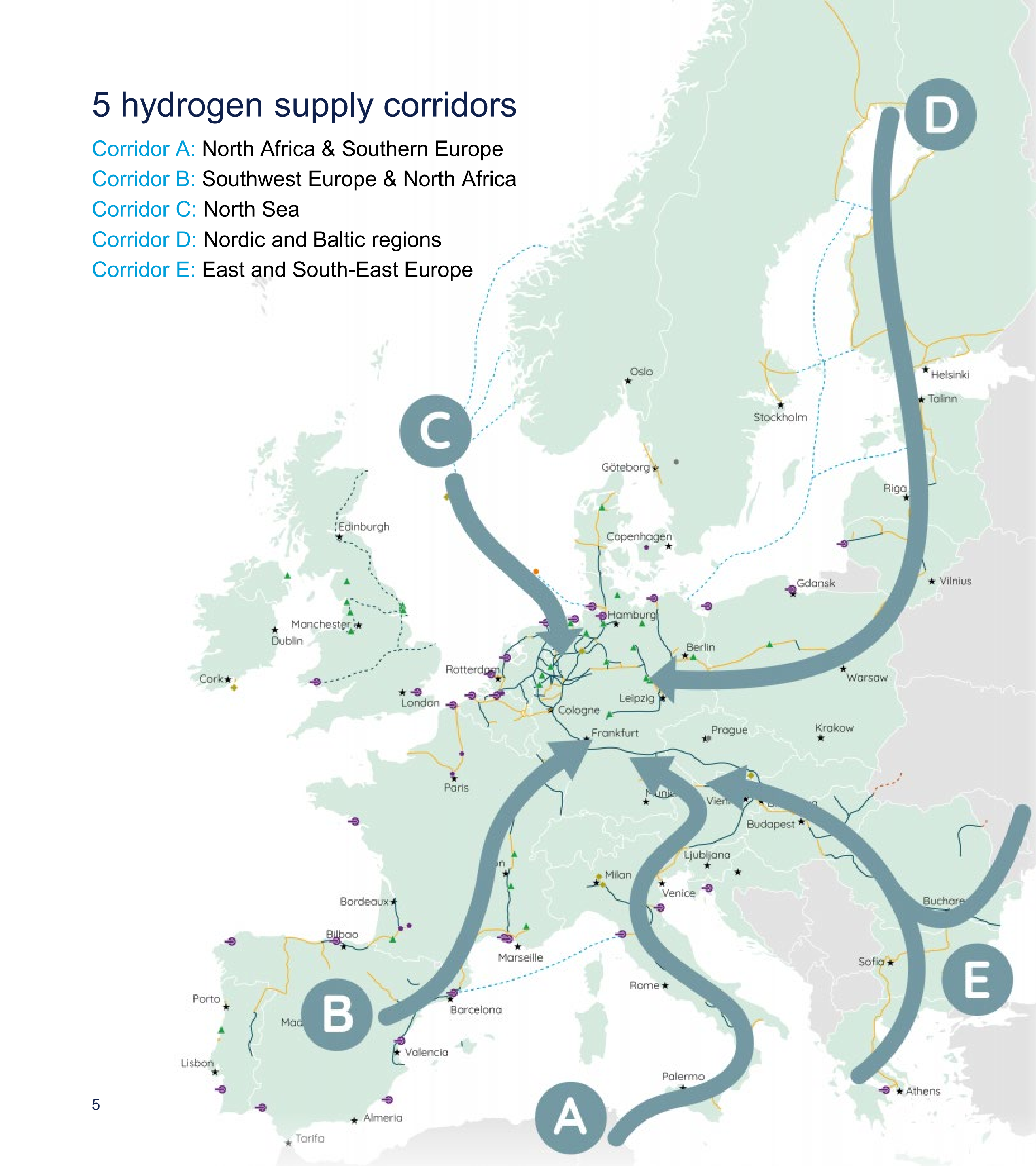
- Denmark has an abundance of natural renewable power sources with an estimated 40 GW of offshore wind[1]
- Predominantly based in the North Sea, excess capacity and curtailed power could generate large volumes of renewable hydrogen
- Potential demand sites for hydrogen are spread across Denmark with pipeline transport up to four times more cost effective than powerlines over large distances[2]
- Variation in supply and batch demand profiles challenges point to point distribution
- Denmark's use of biomass and biogas provides a source of net zero carbon for the generation of further low carbon products from hydrogen
- A hydrogen distribution network could connect supply to demand, linking with storage (line-pack & geological) while unlocking export potential into the European hydrogen backbone[3]

1. Danish Energy Agency, 2019
2. Analysing future demand, supply, and transport of hydrogen, European Hydrogen Backbone June 2021
3. European Hydrogen Backbone, 2020



5 hydrogen supply corridors

Corridor A: North Africa & Southern Europe
Corridor B: Southwest Europe & North Africa
Corridor C: North Sea
Corridor D: Nordic and Baltic regions
Corridor E: East and South-East Europe



Plans to reduce EU dependency on Russia

- Ambition to reduce the EU's Russian gas dependence by two-thirds this year, and to be fully independent well before 2030.
- To achieve this, the EU plan to:
  - Increase energy efficiency
  - Diversify energy supplies
  - Accelerate the roll-out of renewable energy

- The European Commission are accelerating hydrogen uptake in Europe by:
  - Topping-up Horizon Europe investments on the Hydrogen Joint Undertaking (EUR 200 million) to double the number of Hydrogen Valleys
  - Calling on industry to accelerate the work on missing hydrogen standards, for hydrogen production, infrastructure, and end-use appliances

Denmark Supply Build Out – to 2040

Supply

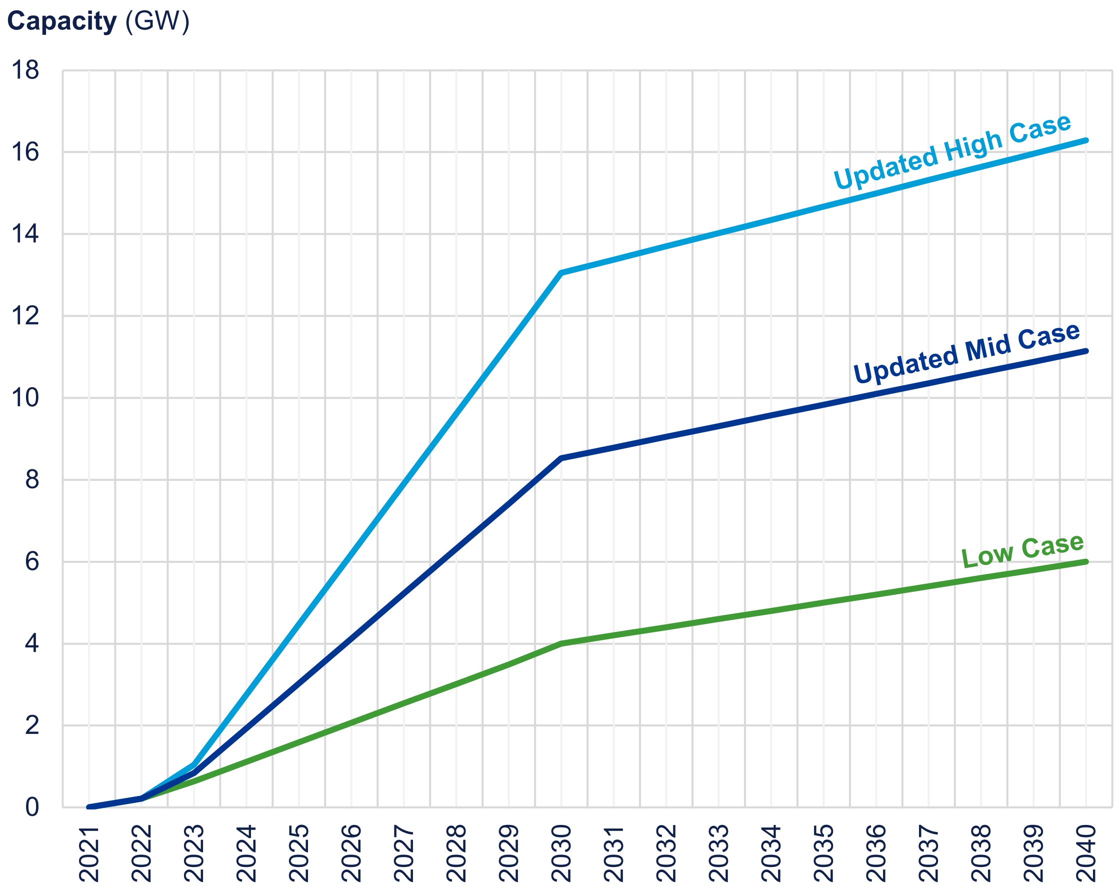
- Owing to Denmark's significant potential for renewable power generation, excess capacity provides a notable opportunity for green hydrogen production
- The Danish Energy Agency (DEA) forecasts a renewable capacity of around 32 GW by 2040, with the majority of offshore production centred around the North Sea and west coast of Denmark. 8 GW (~60%) of 2040 solar capacity is forecasted to be developed in western Denmark
- Existing and future projects in Denmark expect to utilise this renewable power base for hydrogen production, rather than development of blue hydrogen sites, with the largest projects concentrated in industrial locations such as Esbjerg, West Denmark
- There are over 20 announced hydrogen projects being developed in the next ten years, with multiple off-takers in the transport, petrochemical and agriculture industries for conversion to sustainable end products. These projects are at various stages from concept studies through to initial engineering scopes
- An electrolyser capacity forecast was made based on existing forecasts, policy and project phasing to develop low, medium and high supply cases

Planned hydrogen projects and offshore wind developments by 2040

2040 Supply forecast

Since DNV's first assessment at the supply development released earlier this year, new hydrogen projects and additional details for the existing projects have been announced.

- The updated project list from Brintbranchen (the main organisation for Hydrogen and PtX in Denmark) is used to update the original supply cases
  - The majority of the updated capacity comes from the BrintØ project in the Danish North Sea, 10 GW of offshore wind is assumed to correspond to a 6 GW electrolyser capacity
- A new trend line for the planned project build out and phasing is projected to 2040
  - The upper case follows this trendline with the assumption that all of the announced projects reach deployment giving a 2030 capacity of ~13.1 GW, with further growth to 16.3 GW, at a reduced rate, by 2040
  - The lower case follows the Danish Government's latest lower target of 4 GW electrolyser capacity by 2030 with limited growth to 2040 establishing the upper target of 6 GW capacity
  - The medium case follows the mid-point between the low and high cases giving a supply capacity of 11.1 GW by 2040
- Additional supply for the medium and high cases are assumed to be developed in western Denmark based on proximity to future offshore renewable power



Supply Cases	2030 capacity (GW)	2040 capacity (GW)
Low	4.0	6.0
Medium	8.5	11.1
High	13.1	16.3

Denmark Demand Build Out – to 2040

Demand

DNV has assessed the potential demand growth for hydrogen in Denmark across three different deployment options, within each a low, medium and high case has been developed for 2040. Though presented as three combined scenarios the reality may be a mixture of different cases with the low and high case presenting the potential range of 2040 demand.

Export	• Europe – The potential to export excess hydrogen generation via pipeline and link with the planned European hydrogen backbone
Decarbonisation	• Transport – Low carbon fuels for road, maritime and aviation • Power – Decarbonised dispatchable power generation • Heat – Domestic heat in homes to replace natural gas boilers and industrial process heat for use in manufacturing
Replacement	• Refineries – Current hydrogen usage for reduction of oil contaminants • Ammonia – Current hydrogen usage for production

DNV

Demand – Space heating

- Space heating has not been considered a significant demand for hydrogen and was discounted from any modelling
- Denmark's current space heating energy mix is comprised of natural gas, biogas, district heating systems and electrification
- Danish policy and forward forecasting targets an increased use of biogas to phase out natural gas by 2033
- Forecasted energy demand is expected to reduce by 2040 with increasing electrification and district heating systems replacing gas fired space heating
- Danish policy is focussed on biogas generation to replace current natural gas usage, hence there is limited potential for widescale hydrogen deployment for space heating

Blending

Although hydrogen is not expected to be utilised for space heating in Denmark, blending could provide an additional supply opportunity for hydrogen producers as well as short term emissions reductions.

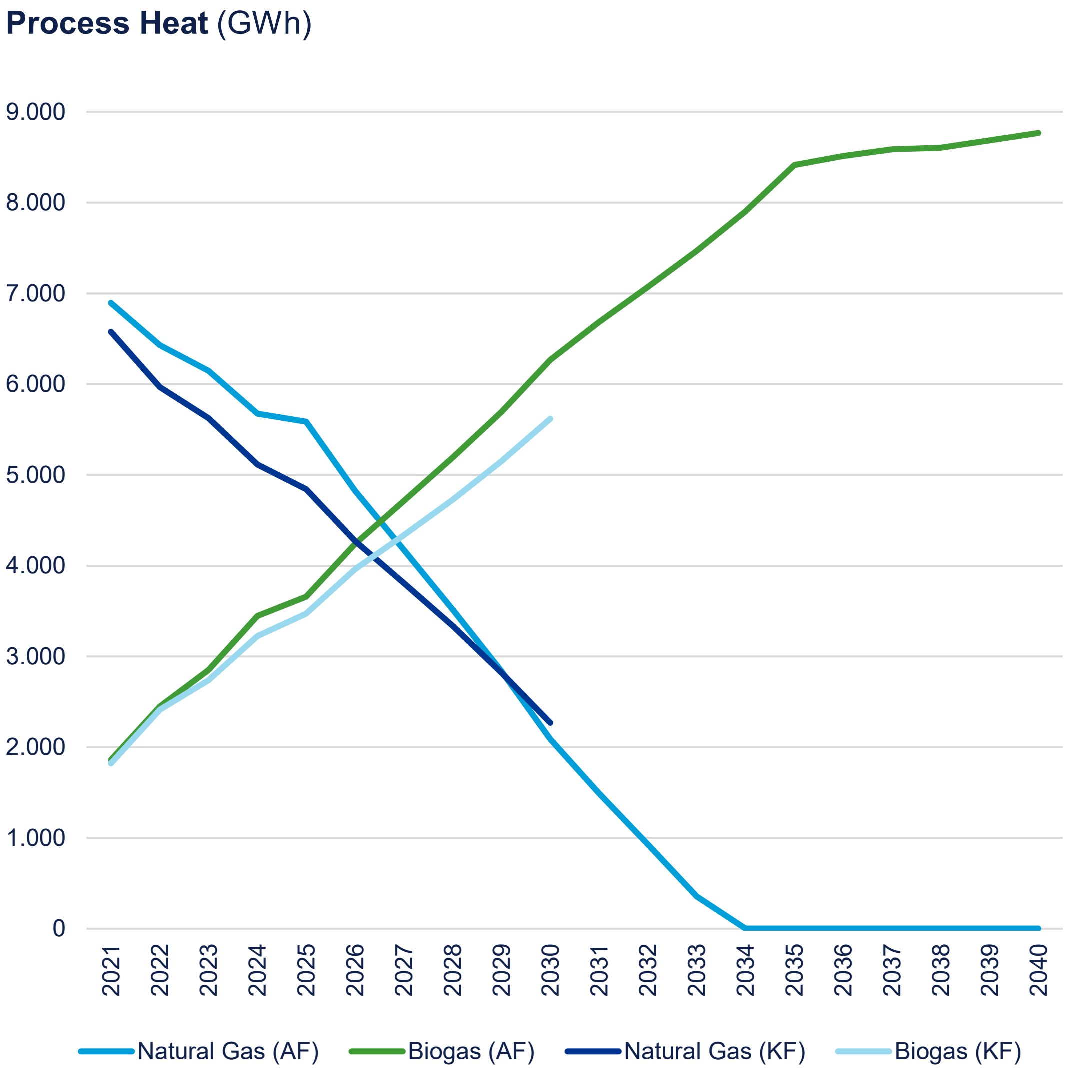
The EU's Hydrogen and Gas markets decarbonisation package published in 2021 suggests gas networks should be ready to allow a 5% blend of hydrogen by 2030[5]. Studies have shown that a 5% hydrogen blend would have minimal disruption to existing infrastructure and end users.

5. EU Commission, COM(2021) 803 on common rules for the internal markets in renewable and natural gases and in hydrogen, 2021

DNV

Demand – Industrial process heat

- The Danish Energy Agency's forward projections target the phasing out of natural gas by 2034 with the energy demand replaced by a supply of biogas
- Total energy demands for industrial process heat are expected to continue at current levels due to electrification's limitations for high temperature process applications
- As Danish policy targets decarbonisation via biogas generation, DNV determined there is low potential for hydrogen deployment for industrial process heat and has not been accounted for in modelling
- This assumption is based on the costs associated with the use of hydrogen for process heat, a biogas switch allows the use of existing assets and downstream equipment
  - A switch to hydrogen would require new assets and equipment at additional cost that would be dependent on hydrogen supplies due to incompatibility with natural or biogas
  - Blending of hydrogen may provide low levels of demand into this sector but the impact of hydrogen on higher pressure systems (compressor design) and burner systems needs to be considered carefully



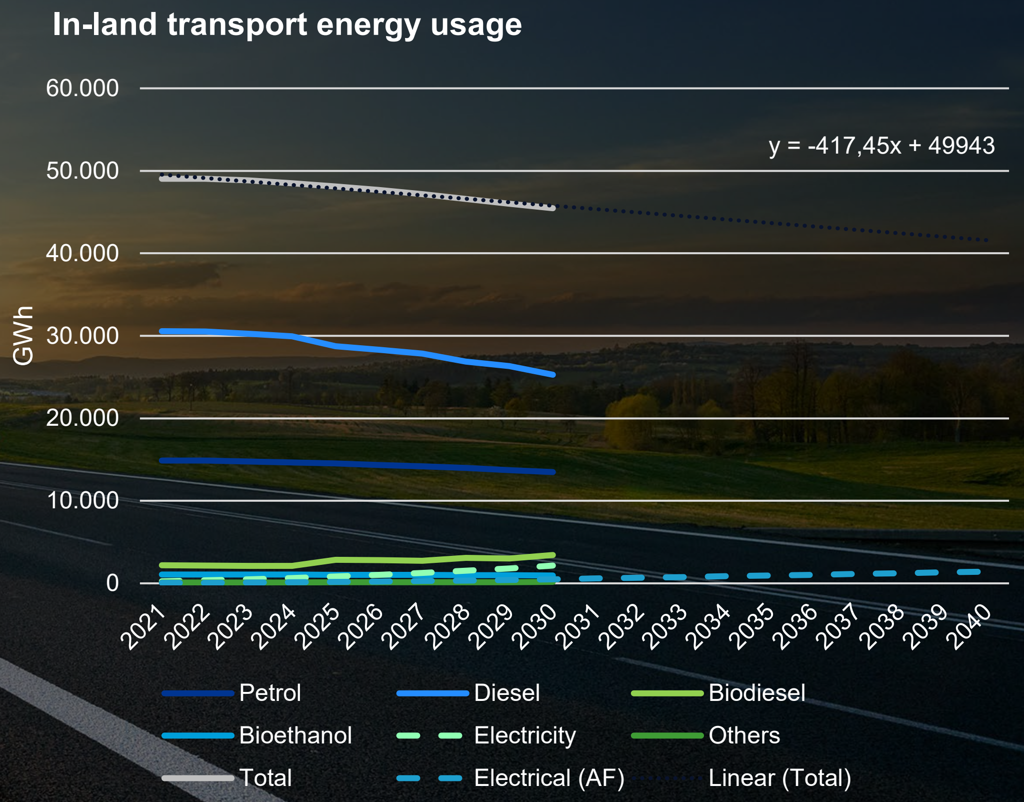
Forecasted process heat demand by fuel type, AF refers to the DEA's Analysis assumptions for Energinet, KF refers to the DEA's Climate and Status projections adopting a frozen policy approach

Demand – Power

- As with commercial and domestic heat the Danish policy and government are targeting the phase out of natural gas fired power with biogas and solid biomass
- This coupled with a growth in renewable power generation limits the opportunity for hydrogen usage in power generation
- DNV assessed the potential for hydrogen to act as a dispatchable power vector for periods of low renewable generation
- With an energy efficiency loss of 75% and the need for investment in dedicated hydrogen power assets, hydrogen for dispatchable generation carries high costs
- Combining this with low uptimes when operating as a dispatchable asset presents considerable commercial barriers
- These may be overcome through government support or the view that hydrogen storage would provide a strategic reserve to manage seasonal swings
- Based on this complexity and availability of alternative options DNV have not considered hydrogen for power generation in this initial assessment

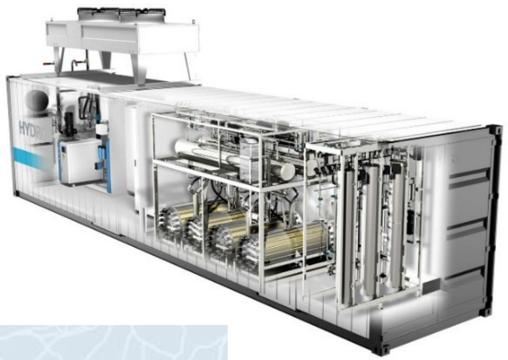
Demand – In-land transport

- Based on the Danish Energy Agency's 2020 forecasts, the total energy demand for in-land transport has been calculated on a continued trajectory of energy efficiency and reduction to 41,594 GWh in 2040
- Based on EU trajectories and cost of deployment, hydrogen fuel cells will have limited role in passenger vehicles and rail
- The main growth in demand is expected to occur in heavier vehicles where hydrogen offers a cost-competitive low carbon fuel source
- 2040 energy demand cases for hydrogen fuels in land transport:
  - Low Case – 4% of energy demand met by hydrogen, based on DNV's 2021 ETO forecasts for in-land transport
  - Medium Case – 11% met by Hydrogen, taken as a midpoint
  - High case – 18% of energy demand met by Hydrogen, this is based on planned Danish projects that specifically target HGV and Buses as end users
- The European Commission has presented the "fit for 55" package that requires at least one hydrogen refuelling station to be available every 150 km along the TEN-T network and in every urban node by the end of 2030



In-land road optionality

- The use of hydrogen in road transport and how fuel stations will meet this demand is still a developing area with two scenarios considered by DNV for this assessment;
  - A hydrogen distribution network supplying refuelling stations
  - Electrolysers based at refuelling sites
- The hydrogen distribution network approach provides end users storage to buffer demand variation but would require purification before end use due to fuel cell quality requirements
- The electrolyser approach would require electrical infrastructure build out to support power requirements alongside hydrogen storage at site to manage high demand cases. Associated footprints and volumes of hydrogen storage would require explosive risk considerations and management
- DNV has assumed for this study that future road demand will be met using a hydrogen distribution network once the infrastructure has been installed, refuelling stations will be based along the chosen topology that aligns with major road networks to reduce infrastructure build out



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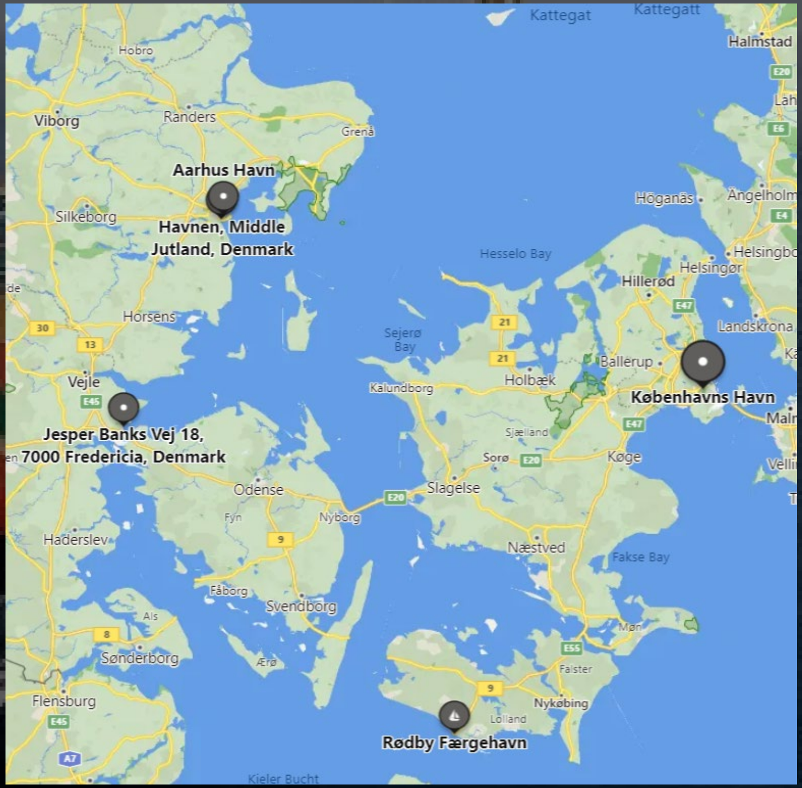
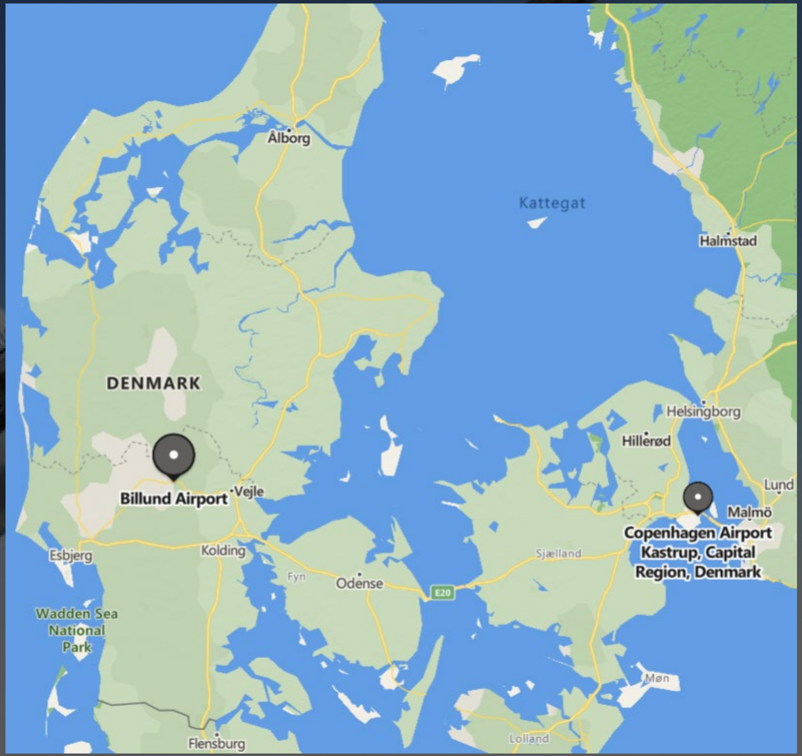
Demand – Marine

- Energy demand is expected to remain flat until 2040. Total domestic shipping was taken from 2019 statistics, and international shipping was taken as a percentage of global trade. The Danish fishing industry's total fuel usage in 2019 was converted to an equivalent energy demand for addition to the domestic freight and passenger movements
- DNV expects that ammonia and methanol fuels will be preferred over hydrogen due to favourable fuel prices and lower investment costs for onboard implementation
- 2040 energy demand cases for Hydrogen-based fuels in maritime shipping:
  - Low Case – 6% of energy demand met by Hydrogen-based fuels, this aligns with DNV's ETO projections for maritime hydrogen demand within Europe
  - Medium Case – 20% of energy demand met by Hydrogen-based fuels, taken as a midpoint between the high and low case
  - High case – 35% of energy demand met by Hydrogen-based fuels, based on the IMO's ambition for a 50 percent reduction in carbon emissions by 2050
- Demand centres have been based on ports with the greatest throughput of passengers and freight with the top ten ports in Denmark accounting for 60% of shipping traffic
- Demand build out has been based on the assumption that clean fuels would be generated at or close to port facilities for bunkering



Demand – Aviation

- Total energy consumption by 2040 to remain stable as efficiency improvements are expected to match increased demand from air traffic
- The government is targeting all domestic flights to be carbon free by 2030
- DNV has assessed international, domestic, and freight movements. Copenhagen Airport accounts for 92% of movements and Billund Airport 8% (assumption is smaller airports will not have enough fuel demand to justify the connection to a hydrogen network)
- 2040 energy demand cases for hydrogen fuels in aviation:
  - Low Case – 11% of energy demand met by hydrogen, this is based on DNV's 2021 ETO forecasts for aviation hydrogen demand across Europe
  - Medium Case – 30% of energy demand met by hydrogen, this is based on the green fuels for Denmark project's target for 2030, medium case assumes this target isn't met until 2040
  - High case – 50% of energy demand met by hydrogen, this is based on achieving the green fuels for Denmark project's 30% target by 2030 with continued linear growth to 2040
- For Copenhagen Airport the generation of hydrogen and demand for synthetic fuel production is assumed to occur to the south of the airport as per the green fuels for Denmark project's initial plans
- For Billund Airport the demand for synthetic fuels is assumed to occur at the Fredericia refinery as an area of industrial development



Green Fuels for Denmark

- Green Fuels for Denmark (GFD) is a flagship PtX project based in Copenhagen aiming to establish a large sustainable fuel production facility
- The project is a partnership with numerous companies including Ørsted, Copenhagen Airports, A.P. Moller-Maersk, Everfuel and Topsoe
- With a combined electrolyser capacity of 1.3 GW by 2030, this is expected to facilitate production of sustainable fuels to account for 30% of Copenhagen Airport's fuel demand, large proportions of heavy vehicle operations in Greater Copenhagen and one container vessel[7]
- Electrolyser developments are expected to be located in close proximity to Copenhagen Airport
- Phase 3 corresponds with plans for offshore wind production from the Bornholm energy island with the electrolysers powered from this resource

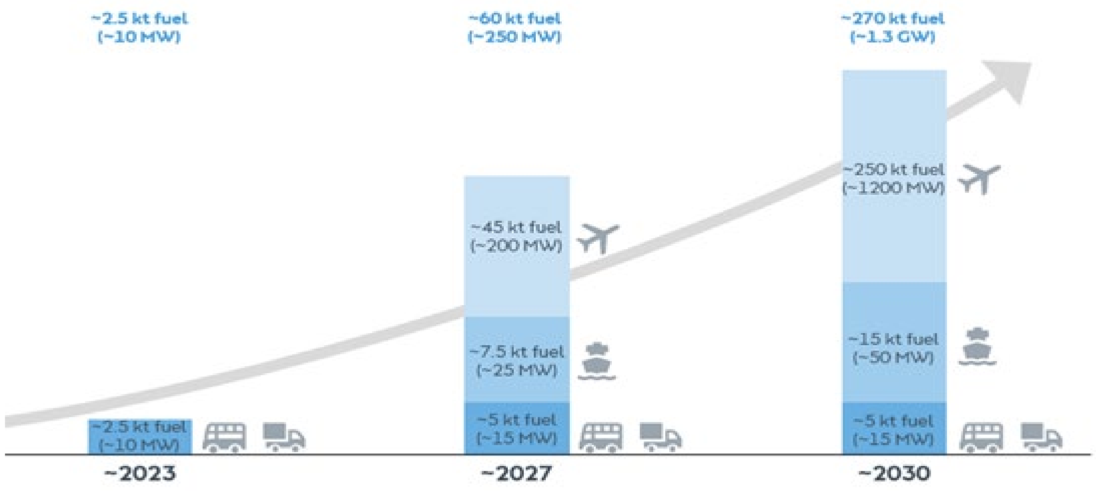
7. Green Fuels for Denmark: Project one pager, Erhvervsstyrelsen, 2021

Planned GFD project phasing, Ørsted (2021)

Phase 1
Develop hydrogen production

Phase 2
Enter carbon to produce maritime and aviation fuel

Phase 3
Scale through aviation demand



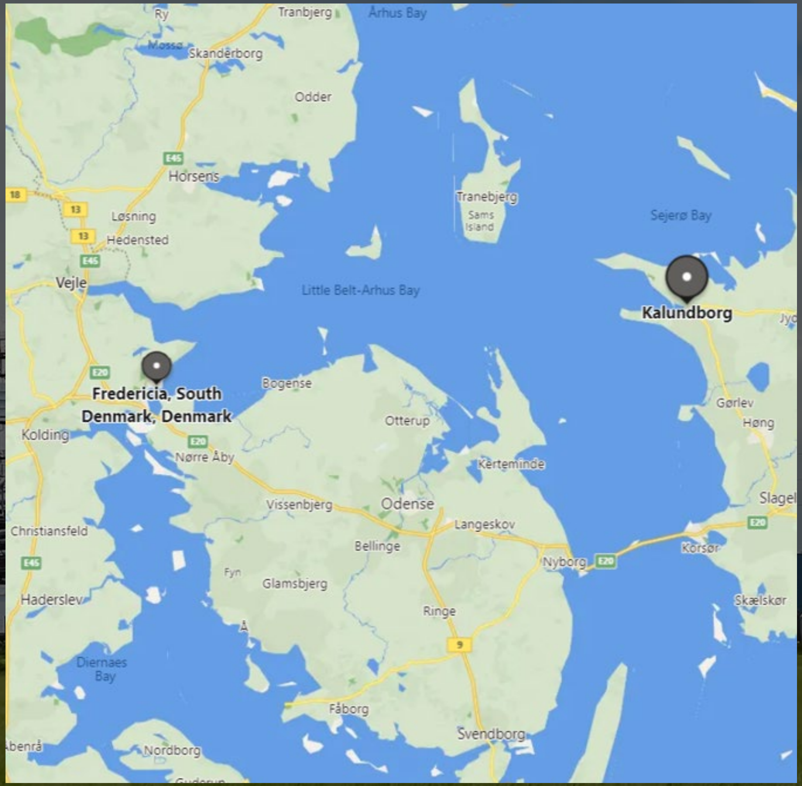
Phase 1 (2023)
is focussed on production capacity of sustainable fuels used in heavy road transport

Phase 2 (2027)
of the project aims to have developed a 250MW electrolyser capacity for the production of ~45kt of Sustainable Aviation fuel (SAF) for decarbonisation of international and domestic aviation. Developers expect phase 2 to account for 5% of Copenhagen Airport's fuel demand

Phase 3 (2030)
plans for a scaling up of combined electrolyser capacity to 1.3 GW corresponding to ~250kt of sustainable aviation fuel. This is expected to cover 30% of demand at Copenhagen Airport.

Demand – Refineries

- Hydrogen demand from Danish refineries in 2018 was equal to 17,625 tons[8] (700 GWh)
- DNV has noted that a percentage of the hydrogen used for Danish refineries is a by-product from the natural gas production in the North Sea due to its high hydrogen content. It is assumed that 50% of hydrogen demand within Danish refineries is met through this by-product rather than traditional steam methane reforming for generation
- Based on our assumption the replacement potential for green Hydrogen is taken at 50% of the total annual demand at 8,813 tons (350 GWh)
- Energy demand cases for hydrogen fuels in refineries:
  - Low Case – 50% of Grey Hydrogen replaced by Green, this is based on the EU's current proposed policies in the renewable energy directive (II) that requires all industrial hydrogen usage to be a mixture of 50% green hydrogen by 2030
  - Medium Case – 75% of Grey Hydrogen replaced by Green, based on achieving the 50% target by 2030 with slower growth out to 2040
  - High case – 100% green hydrogen – based on simplicity of source switch and policy / CO_2 emission costs



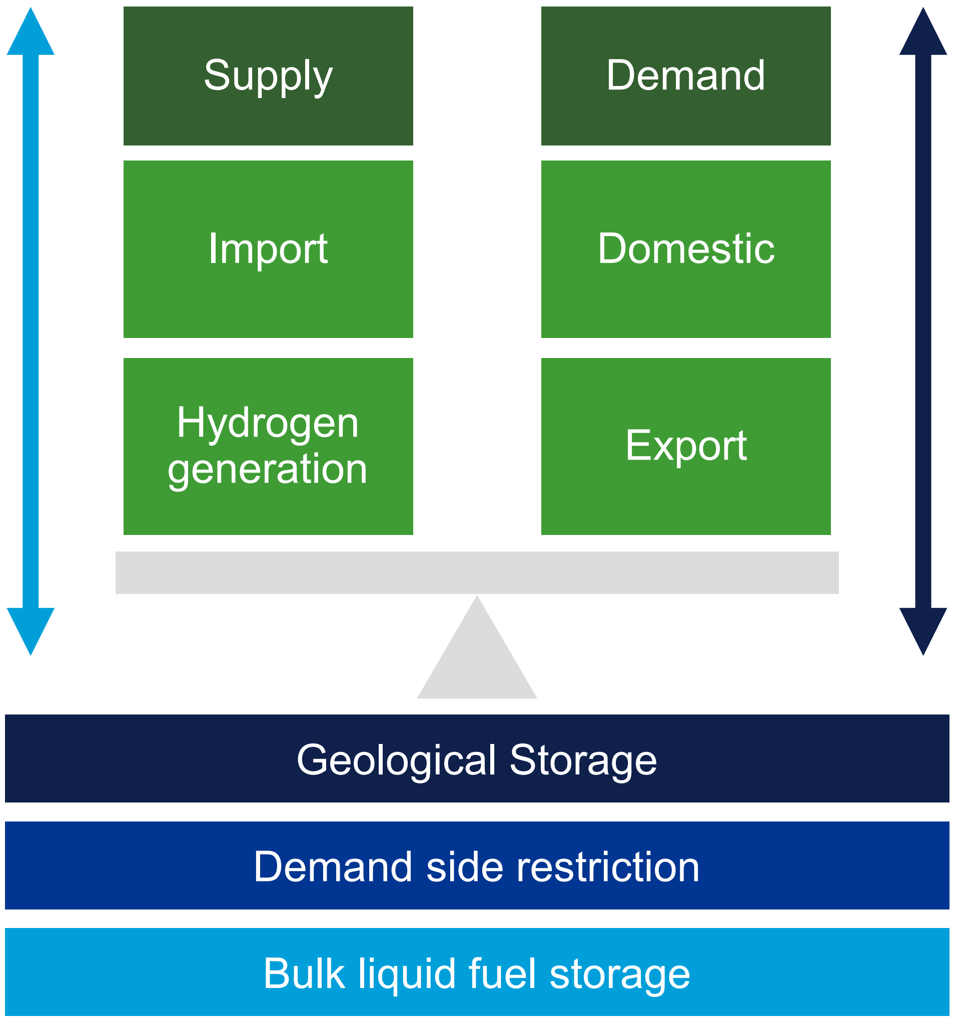
8. Fuel Cells and Hydrogen Observatory, 2021

Demand – Steel and Ammonia

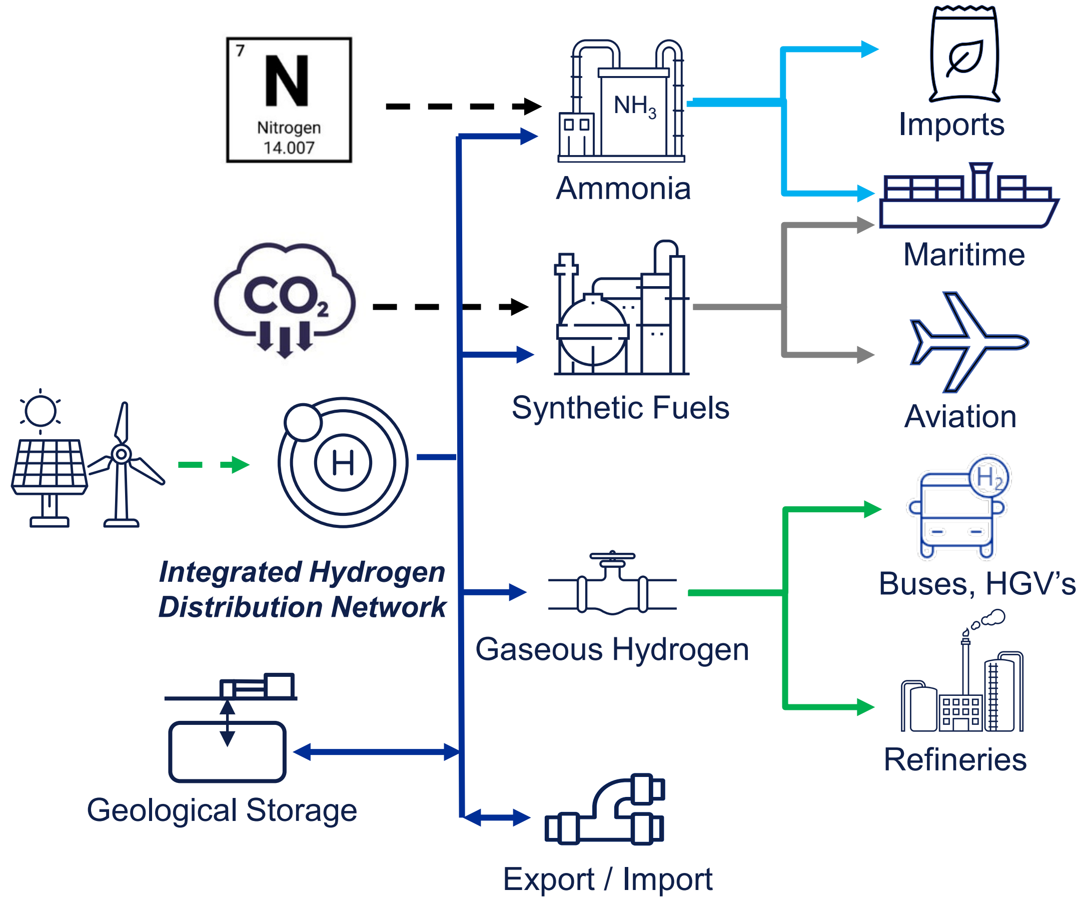
- DNV has assessed the potential to replace domestic ammonia production in Denmark with green hydrogen-based ammonia. Having reviewed emission data and trading volumes, DNV has concluded there is currently no domestic production of ammonia at dedicated sites in Denmark
- Having assessed Denmark's current industry base, DNV has concluded that there are no domestic blast furnace steel works where hydrogen could be deployed as a fuel alternative
- Though domestic ammonia isn't currently produced in Denmark, annual imports totalled 23,000 tons in 2019. It is assumed that this import of ammonia demand could be replaced by domestic green ammonia production, with the increase in supply being based on existing projects planning to target the ammonia market
- Energy demand cases for hydrogen fuels in ammonia sector:
  - Low Case – 0% of imported ammonia replaced by domestic green ammonia, based on continued imports as per historical practice and cost barriers
  - Medium Case – 50% of imported ammonia replaced by domestic green, based on mid case point
  - High case – 100% of imported ammonia replaced by domestic green ammonia, based on high uptake and drive for domestic production
- Location is assumed to be a centralised ammonia production close to a green hydrogen source with further demand distributed as per current imports

System Flexibility

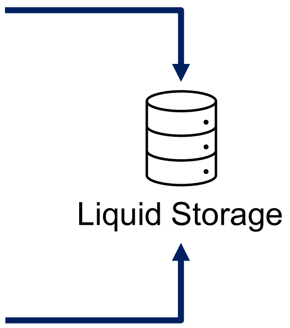
- **Network systems must be designed to manage the extreme cases of supply and demand**, for Denmark this equates to:
  - Full electrolyser load with high supply and minimal domestic demand
  - No supply from electrolysers with high domestic demand
- **Flexibility can be built into the system**, to manage these two cases:
  - **Import / export** – connection into international systems supports both cases but does increase risk through reliance on external infrastructure availability
  - **Geological Storage** – provides a buffer between supply and demand while ensuring security of supply from a domestic asset base
  - **Demand side restriction** – allows demand to be reduced based on a priority list of users to manage supply
  - **Bulk liquid storage** – low carbon fuels such as ammonia, methanol or hydrocarbon liquids (e.g. kerosene as sustainable aviation fuel – SAF) can be stored as liquids in bulk facilities as per current practice for hydrocarbon fuels to smooth supply and demand movements
- **Geological storage and export is scaled to provide the required system balance in initial assessments**
  - Though DNV would envision a mixture of these methods in a future hydrogen distribution system, for simplicity and modelling it has been assumed geological storage and exports



2040 Demand forecast

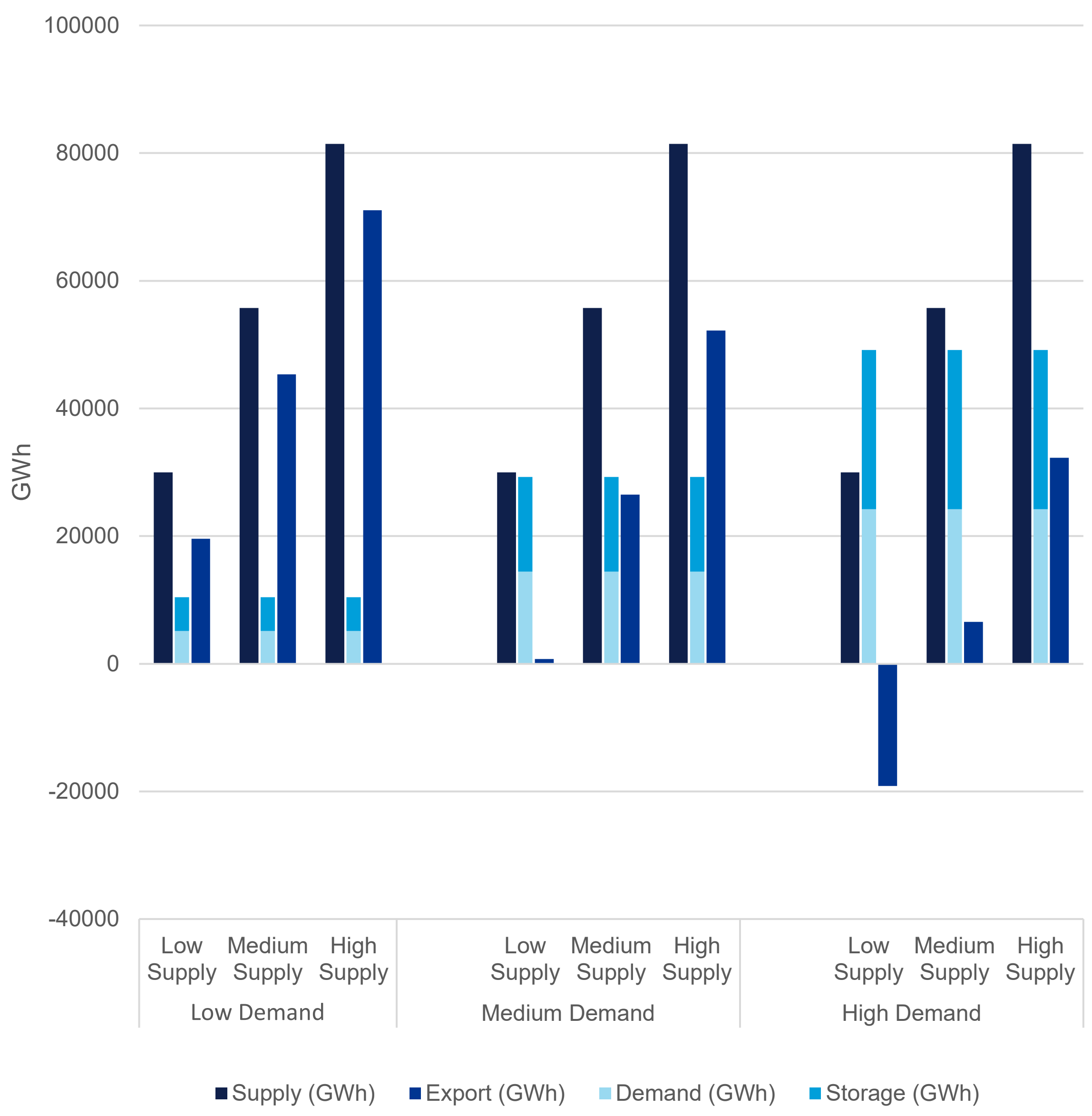


	2040 Demand Cases (GWh)		
	Low	**Medium**	**High**
	0	84	170
	900	3,000	5,200
	2,400	6,500	10,900
	1,700	4,600	7,600
	200	300	400
Total	**5,200**	**14,500**	**24,300**



Hydrogen Storage and Export

- Geological storage offers a strategic reserve within Denmark and prevents reliance on imports or demand side management
- Salt caverns are the only proven storage sites for hydrogen globally (UK, USA) with ongoing pilots and research still assessing the suitability of aquifers or depleted hydrocarbon fields
- Lille Torup's current storage is expected to be required for natural gas and biogas as the infrastructure transitions
- Expansion of this storage for hydrogen storage could scale to cover demand cases with low supply (assumes required size and geology is available)
- In cases where supply exceeds domestic demand it is assumed storage takes priority (though price may impact this), excess capacity is then exported into Germany
- This export route would allow connection into the proposed European hydrogen backbone at Hamburg (2030) unlocking an EU wide system of hydrogen storage and distribution



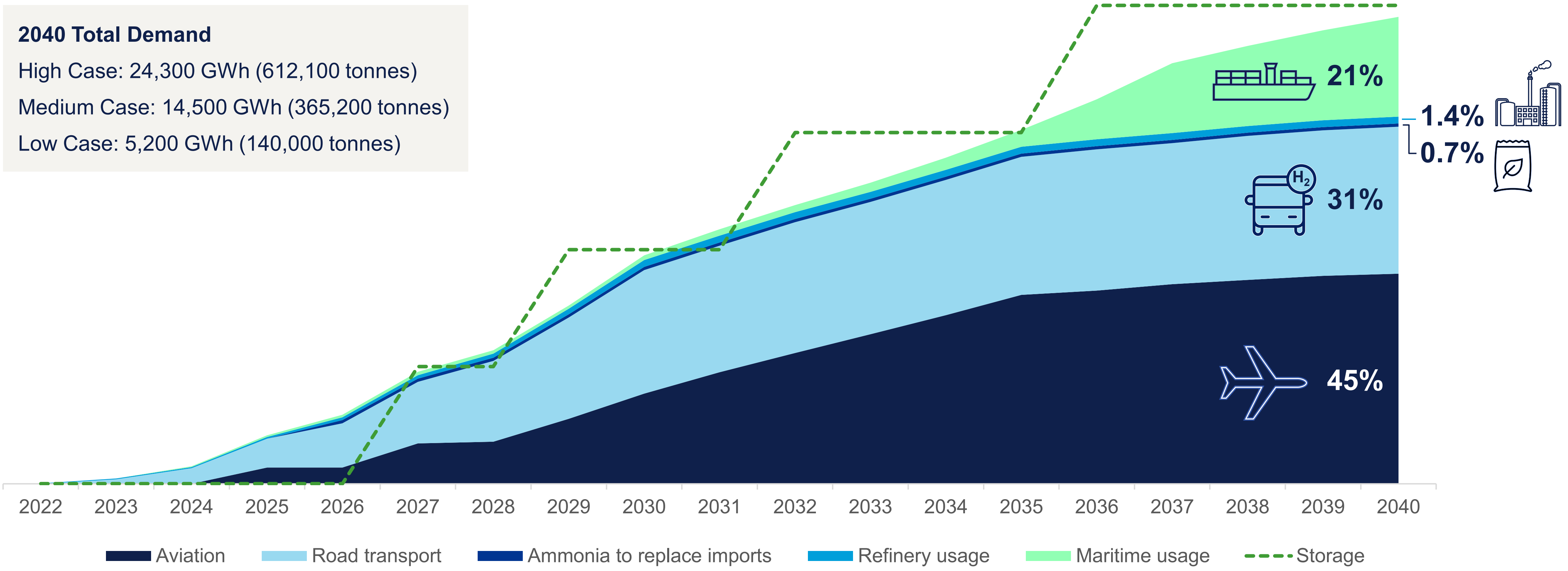
Demand Build Out – to 2040

2040 Total Demand

High Case: 24,300 GWh (612,100 tonnes)

Medium Case: 14,500 GWh (365,200 tonnes)

Low Case: 5,200 GWh (140,000 tonnes)



HHV for Hydrogen: 39.7 kWh/kg

Demand Build Out – to 2040

Aviation

Hydrogen demand for the aviation sector continues its growth out to 2040, as the conversion of older fossil fuel-based systems continues to decline to meet net zero targets.

This will make up 45% of the total Danish hydrogen demand in 2040, reflecting Denmark's ambition for fossil fuel-free aviation.

Road

Heavy transport continues its growth out to 2040 as demand and conversion of older fossil fuel-based systems continues to meet net zero targets.

This will make up 31% of the total Danish hydrogen demand in 2040.

Ammonia

Due to the step change forecast for 2026, meeting 100% of the demand in 2040 there is no further build out for ammonia imports.

This will make up 0.7% of the total hydrogen demand within Denmark, in 2040.

Refinery

The rapid role out of grey hydrogen replacement in refineries means that 100% of the demand in 2040 is met by 2030.

This will make up 1.4% of the total hydrogen demand within Denmark, in 2040.

Maritime

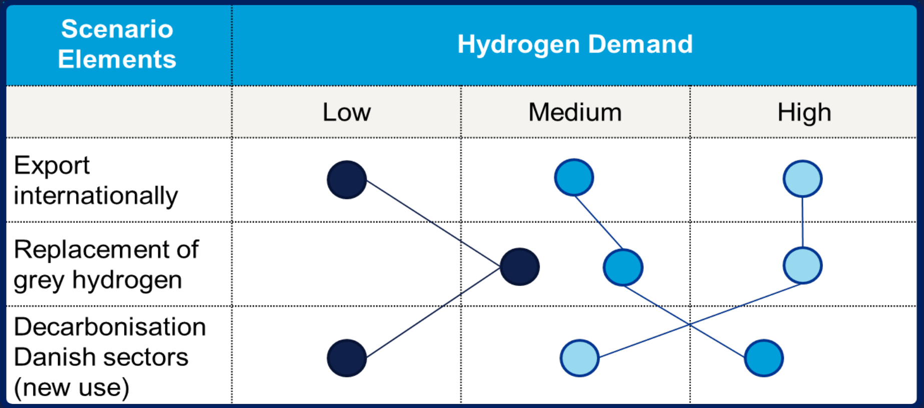
From 2035 to 2040 the maritime sector expands rapidly with conversion of international and domestic fleets to low carbon fuel sources with the development and deployment of technologies to manage the hazardous challenges of these alternative fuels.

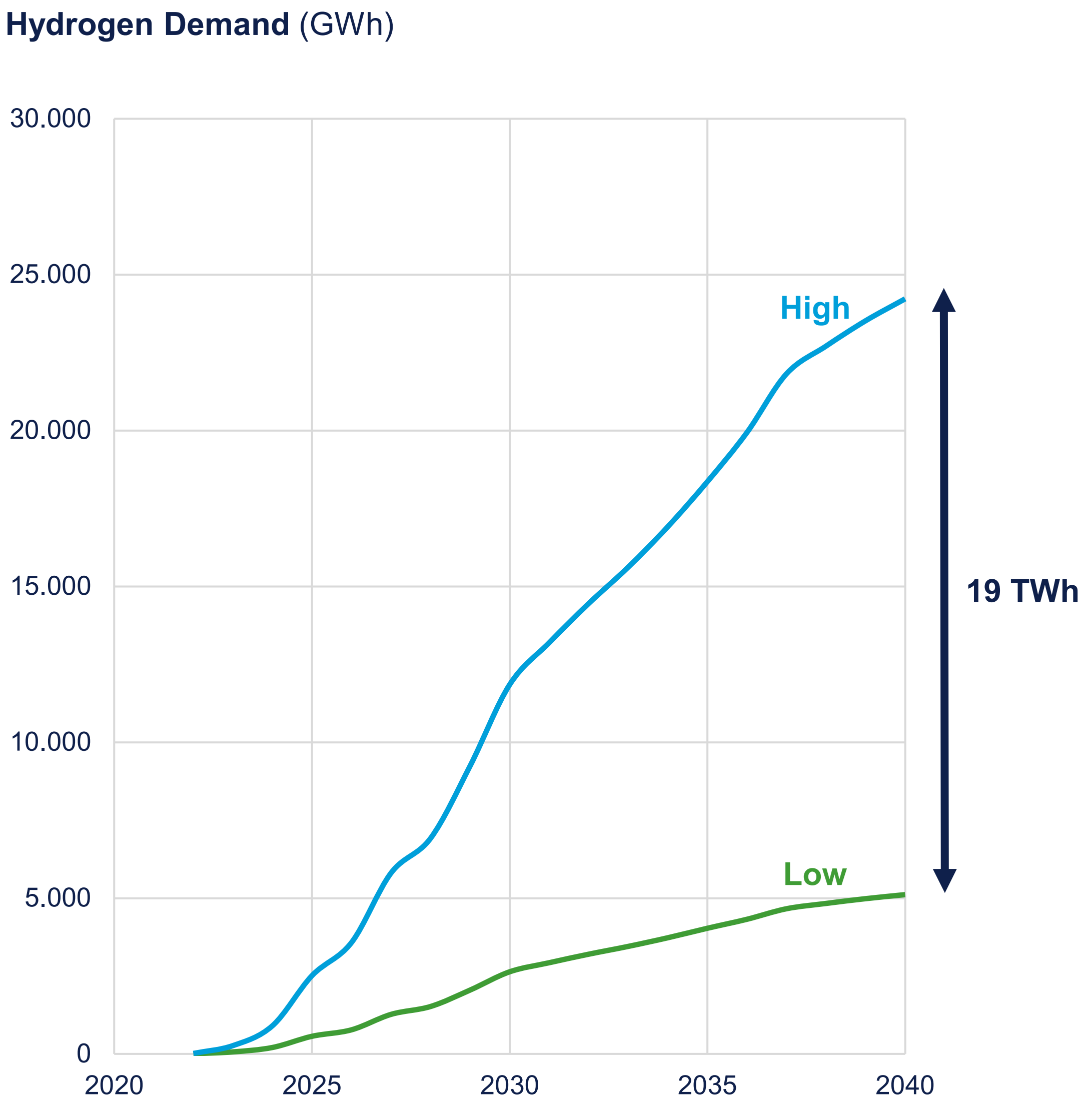
Established bunkering and port facilities globally provide confidence for ship operators to convert stock while new LNG fuelled ships approach end of operational life.

DNV

Hydrogen demand scenario limits

- DNV's forecasted high and low cases provide the upper and lower limits of potential hydrogen demand across the sectors identified
- This represents a potential of 19 TWh of variation by 2040 across export, replacement and decarbonisation deployments depending on their future build out





Upper and lower Hydrogen demand build outs for the high and low cases by 2040

Conclusions (1/2)
Work package 1

- Denmark has a strong potential to develop itself as a European leader in hydrogen generation and low carbon products due to its abundance of renewable generation and biomass / waste power generation for capture of carbon neutral CO_2
- Domestic demand has potential to see significant growth in alternative fuel for transport across aviation, marine and road (buses, HGVs) by 2040
- The road sector will provide the initial demand growth in transport due to high technology readiness levels, this is quickly followed by aviation with the ability to use synthetic fuels in existing engines
- The marine sector demand growth accelerates in 2035 due to technology development barriers for low carbon fuels coupled with the long asset lifetime of ships
- Replacement of hydrogen in refineries and ammonia imports provides additional small scale demand
- An interconnected hydrogen distribution system would enable stable supply to demand centres while unlocking the potential for export into Europe
- Balancing of the network during low supply could use a range of options across import, geological storage, demand side management and bulk liquid storage

Conclusions (2/2)
Work package 1

- Geological storage in salt caverns at Lille Torup could provide the required balance for the system while ensuring security of supply for Denmark
- Denmark's phase out of natural gas by 2033 is based on a switch to biogas across its heating, power and industrial sites. Hydrogen could have a role to play in supporting this transition if biogas is unable to scale at the pace required but would need to consider downstream users and impacts on equipment / materials
- The growth and bulk storage of low carbon marine fuels will need to consider the lower energy content and higher frequency of bunkering required in comparison to heavy marine oils
- Current land based electrolysers carry a high footprint (1 MWe equal to 32 - 48 m^2) with the requirement for a potable water source potentially restricting their deployment and scale, future designs are targeting more compact designs and stackable facilities
- Refineries require hydrogen to remove contaminates from crude oil, this demand may decrease in the future as demand for oil derivatives declines

Abbreviations

Abbreviation	Meaning
BECCS	Bioenergy Carbon Capture and Storage
ETO	Energy Transition Outlook
DEA	Danish Energy Agency
GFD	Green Fuels for Denmark
HGV	Heavy Goods Vehicle
HHV	Higher Heating Value
IMO	International Maritime Organisation
NG	Natural Gas
PtX	Power-to-X
SAF	Sustainable aviation fuel

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