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RENEWABLE ENERGY RESEARCH & ADVISORY

Content

Who we are

INDUSTRY EXPERTS

Our team consists of experienced individuals from leading energy consulting firms combined with industry professionals. Our management team alone has a combined 80+ years of industry experience.

POWERFUL DATA

We have a team of data and analytical experts from renewable energy backgrounds. Their research expertise drives our databases and makes us a preferred partner for providing advice and aiding strategic and operational decision-making.

CONNECTING DOTS

Our strong ability to connect the dots in a dynamic and rapidly developing business provides our clients transparency across options and a basis for informed decision-making by providing data, intel, and actionable advice.

STRONG NETWORK

We work within a well-developed professional network with a proven track record covering the entire renewable energy infrastructure lifecycle, combined with our knowledge of local markets and years of experience.

What we do

SECTORS OF EXPERTISE

ONSHORE WIND

OFFSHORE WIND

SOLAR PV

H2 & POWER TO X

OFFERINGS

CONSULTING

MARKET

TECHNOLOGY & SUPPLY CHAIN

TRANSACTIONAL

RESEARCH

WIND POWER
ONSHORE
OFFSHORE

GREEN HYDROGEN

Content

H2 Data Catalogue

CIP Fonden

March 2023

CIP fonden

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Scope and foundation

Reliance

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Sources of information

In conducting this report, Brinckmann Group (Brinckmann) has relied on any written documentation provided by the Client, publicly available information, various analyst reports, industry expert interviews, Brinckmann databases and analysis.

Validation

In completing the report, Brinckmann has relied on the integrity of any data that has been provided by the Client and has been obtained through the sources of information as specified in the report.

Brinckmann has assumed that any information provided by the Client is true, accurate and not misleading and consequently no independent verification of such information has been carried out.

Date of the Report

Work was completed on 07.02.2023. Background data used for this report is based on information received from the Client and research and data in Brinckmann's possession as of the forementioned work completion date. Events and conditions which occur after this date may compromise the results in a material way.

Estimation

Due to data availability and the forward-looking nature of Brinckmann's analysis, some of this report's data rely on Brinckmann's estimates. Brinckmann has taken due care in producing the estimates, but Brinckmann takes no responsibility for these estimates or their accuracy.

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Energy islands unlock large scale offshore wind potential while optimizing hydrogen production

Energy islands in short

The concept of an energy island covers the definition of an existing island, the construction of an artificial island or a platform based island, serving as a hub for energy distribution from surrounding offshore wind farms.

- As part of the Danish climate agreement for energy and industry of June 2020 it was agreed to begin the construction of the world’s first two energy islands in Denmark
- The energy islands are considered pioneering projects that potentially could be the key to unlock the rapid and unprecedented build-out of offshore wind

DK Island I: North Sea Energy Island: <10 GW Offshore wind

- Will be located ~80 km from western shore of Denmark
- Expected to feed electricity to United Kingdom, Norway, Netherlands, Germany and Denmark

DK Island II: Baltic Energy Island: 3 GW Offshore wind

- Wind farms will be installed near shore (~15 km.)
- Expected to feed electricity to an energy plant on shore, which then will transform and distribute power to Germany and other parts of Denmark

Benefits from energy islands and offshore hydrogen production

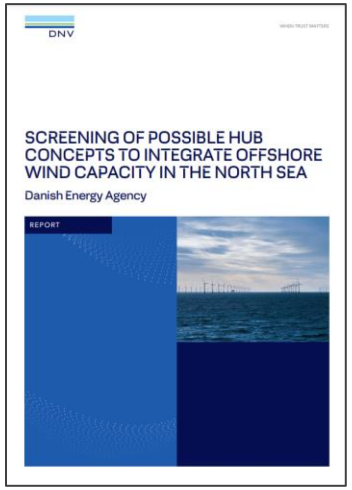
Various analysis and assessments have been carried out in order to establish transparency on the potential from Energy Islands. One key topic discussed across reports is offshore production of hydrogen from electrolysis technology.

Three reports have been reviewed to summarize the findings on upstream hydrogen production:

1) DNV, Screening of possible hub concepts to integrate offshore wind capacity in the North Sea (2020)
2) Energinet, Systemperspektivanalyse (2022)
3) DTU, Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs (2021)

Key take out

- Upstream Hydrogen production (at Energy Island) represent a cost optimized opportunity for hydrogen production
- Gains are driven by increased end-to-end system efficiency and cost savings




Renewable and Sustainable Energy Transition

Onshore, offshore or in-turbine electrolysis? Techno-economic overview of alternative integration designs for green hydrogen production into Offshore Wind Power Hubs

Cost savings in electrical infrastructure more than outweigh the additional cost of moving electrolysers offshore

DNV report made for Danish Energy Agency[1]

In this analysis, four different concepts of energy hubs (electrical and hydrogen) were accessed, comparing onshore vs. offshore hydrogen production. Key findings:

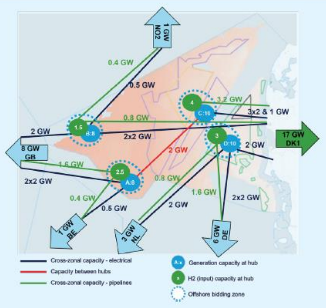
- *"…whilst offshore electrolysers are expected to be more expensive than their onshore counterparts, the savings from avoiding the need to build some of the HVDC converters are of a much larger scale"*
- *"…onshore hydrogen production in the centralized concept led to a much higher LCOE. Hence, we conclude the location of hydrogen production to be a dominant factor"*
- *"Concept 2 which is an offshore hybrid concept where the renewable energy can be evacuated both as electrons and molecules gives the second highest results"*
- *"Concept 3 results in the highest power system utilization… …This is likely due to the fact that Concept 3 has the lowest levels of curtailment among the concepts"*

DRIVER I:

LOCATION OF ELECTROLYSIS – ONSHORE VS. OFFSHORE

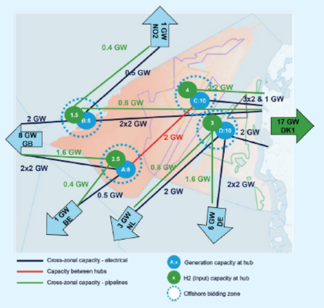
DRIVER II:

UTILYZATION OF ELECTROLYSIS CAPACITY



Characteristics	Concept 2
Number and size of hubs	2 hubs of 10 GW each 2 hubs of 8 GW each
Total cable length (km) per capacity level	Cable 2 GW > 2877 Cable 1.5 GW > 0 Cable 1 GW > 0 Cable 0.5 GW > 813
Total pipeline length (km) per capacity level	Pipeline 0.4 GW > 813 Pipeline 0.8 GW > 533 Pipeline 1.6 GW > 657 Pipeline 3.2 GW > 76
Electrolysers location	Offshore
Electrolyser powered by	Offshore wind farms (hubs), and energy from the wider grid

Figure 2-8 Detailed 'Centralised - Hydrogen offshore - Combined Hydrogen and Electrical' concept



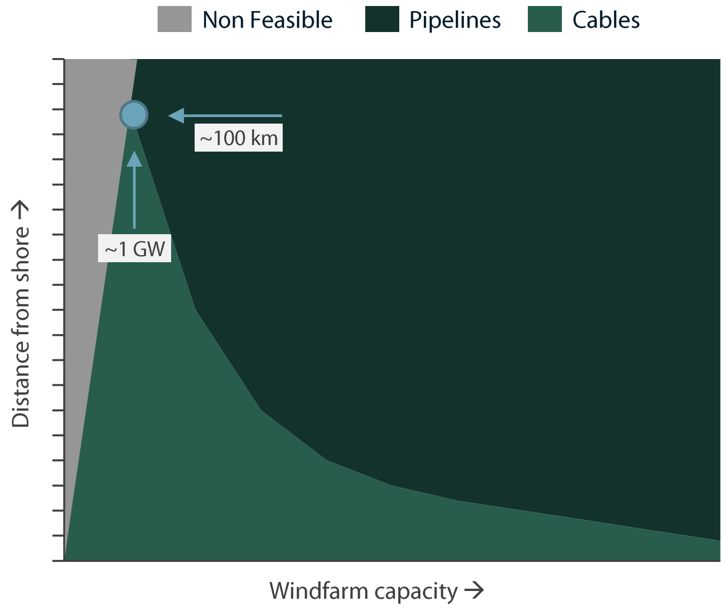
Characteristics	Concept 3
Number and size of hubs	2 hubs of 10 GW each 2 hubs of 8 GW each
Total cable length (km) per capacity level	Cable 2 GW > 2877 Cable 1.5 GW > 0 Cable 1 GW > 0 Cable 0.5 GW > 813
Total pipeline length (km) per capacity level	Pipeline 0.4 GW > 813 Pipeline 0.8 GW > 533 Pipeline 1.6 GW > 657 Pipeline 3.2 GW > 76
Electrolysers location	Offshore
Electrolyser powered by	Dedicated offshore wind farms (within the hubs)

Figure 2-9 Detailed 'Centralised Hubs - Combined Hydrogen and Electrical Topology - Electrical generation reserved for electrolysers' concept

Supporting findings – DNV-GL: Hydrogen and Offshore Wind[2]

In the report Hydrogen and Offshore Wind[2] it is concluded that upstream generation and transmission of hydrogen is superior in comparison to downstream conversion, w. electrolysis placed onshore, in scenarios where the following apply:

- Distance to shore: >100km
- Offshore wind capacity: >1GW



1) DNV-GL: Screening of possible hub concepts to integrate offshore wind capacity in the North Sea. 2) DNV-GL: Hydrogen and Offshore Wind.

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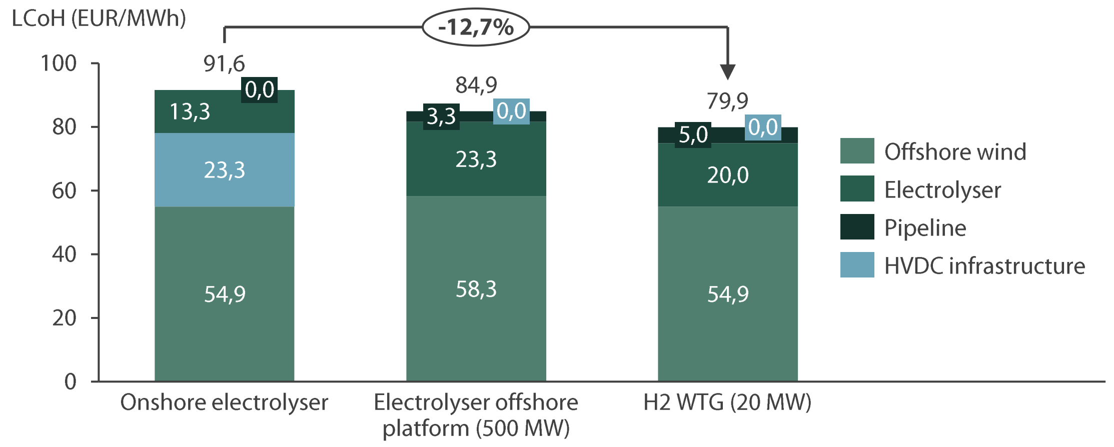
Upstream energy conversion increase system efficiency and reduces energy transport costs

Energinet: Systemperspektivanalyse 2022[1]

In this analysis, levelized cost of producing Hydrogen (LCoH) is compared across three scenarios of which two features upstream conversion based on electrolysis, 100 km. from shore. Key findings:

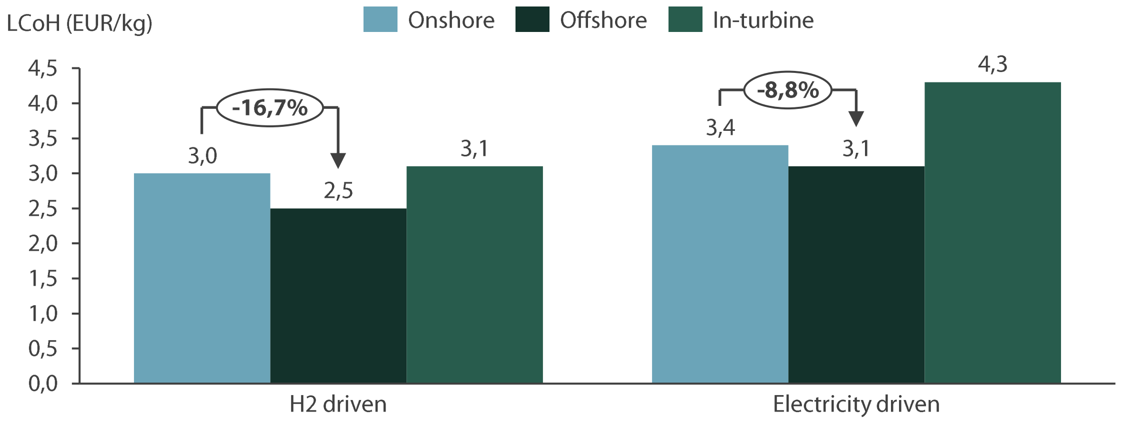
- It is more costly to transport energy from sea to shore by electrical infrastructure compared to hydrogen infrastructure
- For offshore turbines near shore (<50 km) onshore electrolyser is the cheapest hydrogen solution
- Figure 13 in the report (replicated below) concludes ~13% lower costs by moving Hydrogen production upstream, locating the electrolysis at the Offshore WTG



DTU: Onshore, offshore or in-turbine electrolysis?[2]

The DTU report conducted an analysis of LCoH across different setups with electricity generated by offshore windfarms. Key findings:

- Dedicated H2 driven turbines will provide the lowest LCoH compared to electricity driven turbines
- The report found that the lowest LCoH was achieved by placing the electrolyser offshore (~17% cheaper than onshore electrolyser)
- The LCoH for H2 WTG's is penalised by limited economies of scale compared to larger plants onshore and offshore



1) Energinet: Systemperspektivanalyse 2022 **2)** DTU, Onshore, offshore or in-turbine electrolysis? (2022)

Energy island hydrogen production enables economies of scale compared to hydrogen plants located onshore

Key findings

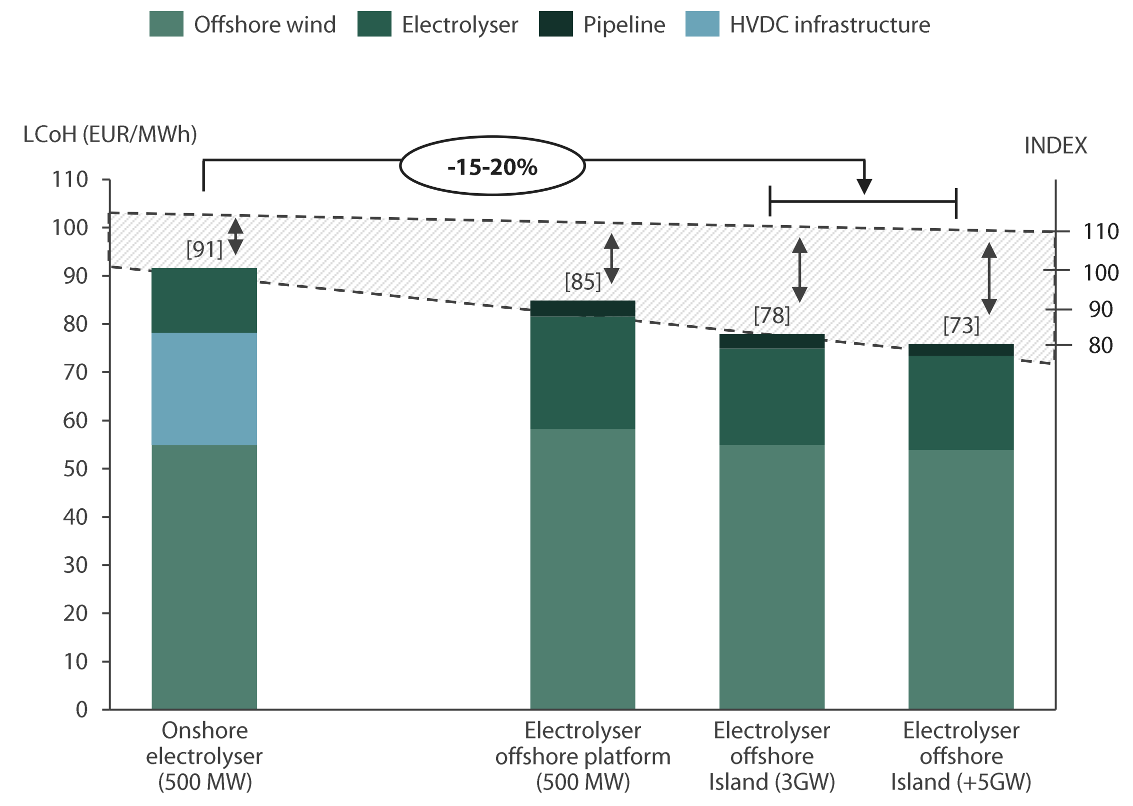
Reports from DNV, Energinet and DTU provide evidence for economical advantages enabled by upstream conversion of energy, by moving the electrolyser-equipment offshore.

While Energinet and DTU do not agree about the financial feasibility of H2 turbines, all reports are finding evidence for cost savings in the range of 13%-17% by moving electrolyser offshore.

An analysis conducted by Brinckmann supports an optimized LCoH by co-locating electricity generation and consumption.

- Main contributor to cost savings is the removal of HVDC equipment and replacing it with pipeline infrastructure
- Increase in energy efficiency by moving generation and consumption closer together
- To fully unlock the offshore potential, scale is key. For offshore hydrogen production there exists a large economies of scale for the electrolyser and for the pipeline infrastructure.

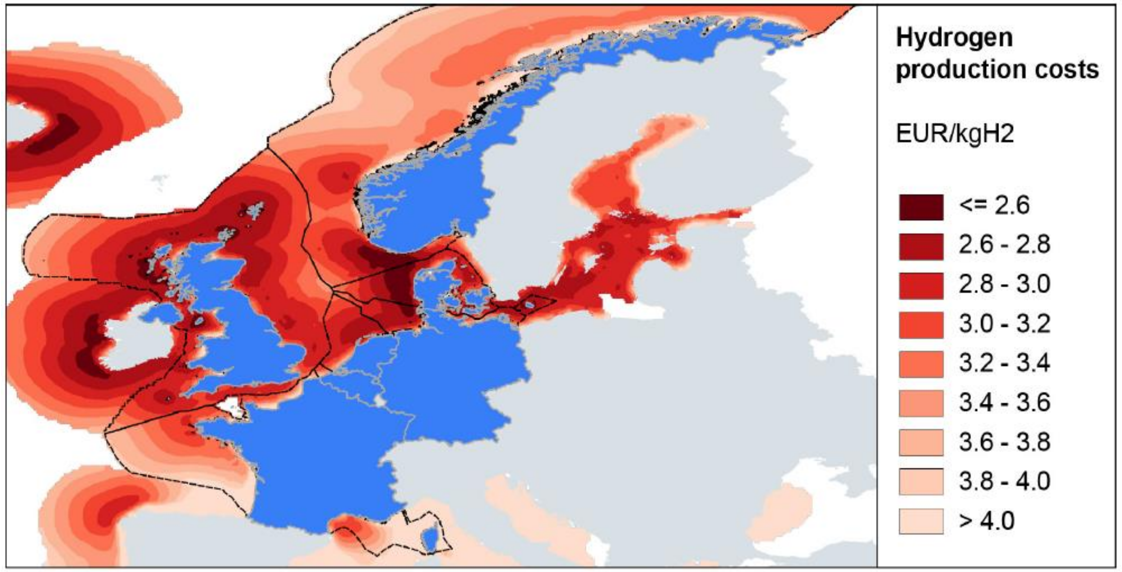
LCoH – cost optimization by moving electrolyser-equipment offshore[1]



1) Brinckmann

Danish territory enables cost advantage over Germany for hydrogen production, scale is a key driver

EIA: Hydrogen production costs from offshore wind in the Accelerated scenario, 2030



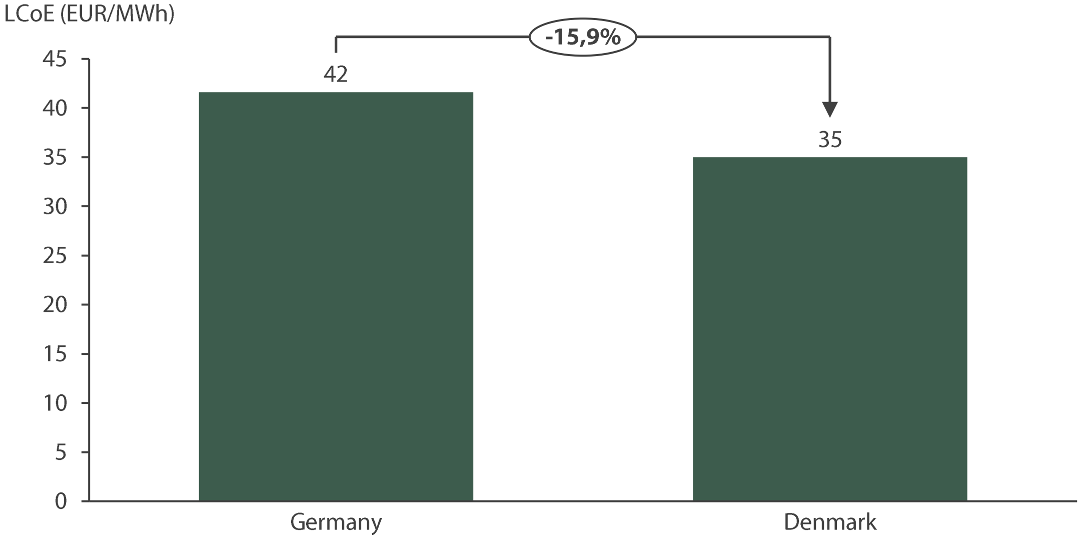
The analysis from EIA maps out the attractiveness of the European sea bed in respect to LCoH potential.

- A large share of the most attractive area is located in Danish territory
- The zone with lowest production costs (<=2,6 EUR/kg) accounts for ~50% of the total Danish EEZ, while it is less than 10% of the German zone

DEA: Offshore wind potential in the North Sea

The analysis conducted by the Danish Energy Agency in 2022 found LCoE levels for Danish offshore installations to be ~16% lower compared to the German installations.

- The report found that the differences in LCoE levels are expected to give Denmark the position as net exporter of offshore energy, whereas Germany is expected to become net importer of offshore energy.



Cost-advantages from offshore generation of energy suggest increased future energy-flows across the DK/DE border

Key take out

In terms of generation of offshore energy, sea bed conditions and wind speed are key factors, both varying significantly across the North Sea nations.

The conditions in the Danish offshore zone are some of the best for offshore energy production giving Denmark an advantage to become net exporter of offshore energy.

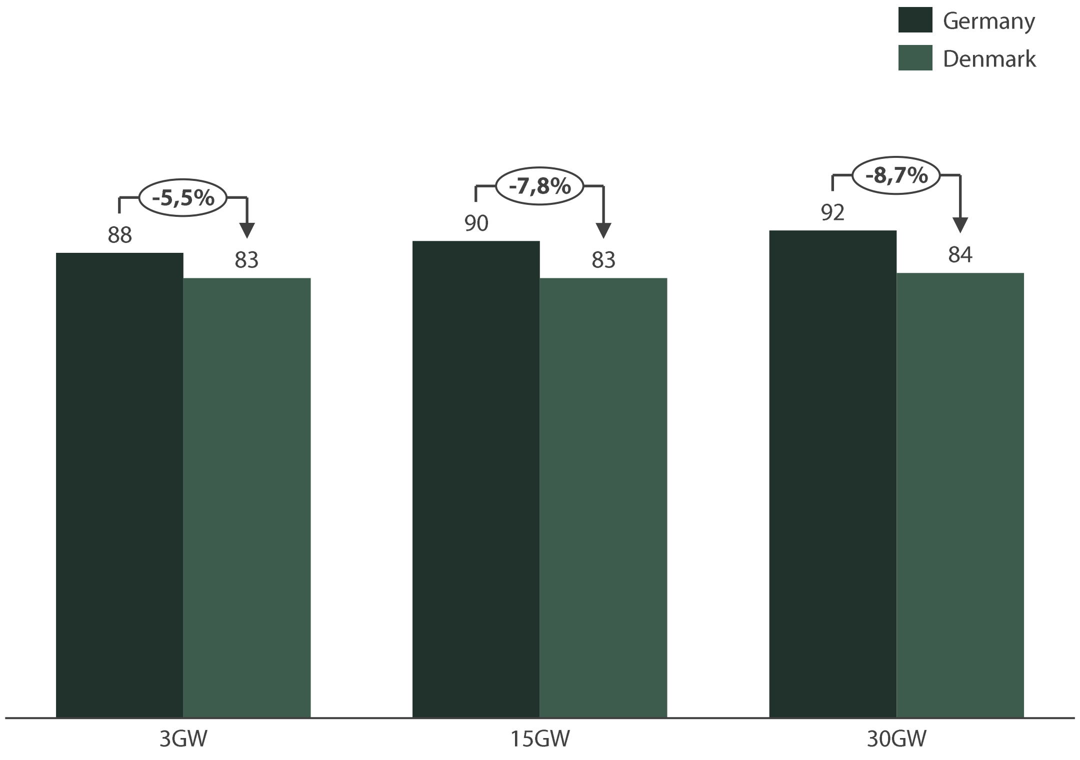
In comparison to Germany, being forecasted as a net energy importer, Denmark's cost-advantages from large scale offshore generation of energy suggest a potential increase in energy-flow across the DK/DE border.

A simulation based on the IEA map presented at p. 13, suggest the following scale effects, considering existing Offshore installations in Germany and Denmark.

- By 2022 Germany had an installed capacity of ~8GW Offshore wind, primarily located in the most attractive area, and hereby exhausting the German 'low cost' zone
- By comparison, the Danish 'low cost' zone is significantly larger and is asses to hold a potential of ~35GW
- Reflecting, that the German 'low cost' zone is occupied by the installed fleet of Offshore wind, a base LCoH delta is expected at approx. 5-6%
- Considering German ambitions to continued increasing the share of Offshore wind in the electricity-mix, electricity generation is forecasted to have preference over Offshore Hydrogen production, hereby further increasing the Danish LCoH advantage

Danish EEZ holds a significant advantage over Germany

LCoH delta between Denmark and Germany increases with scale.

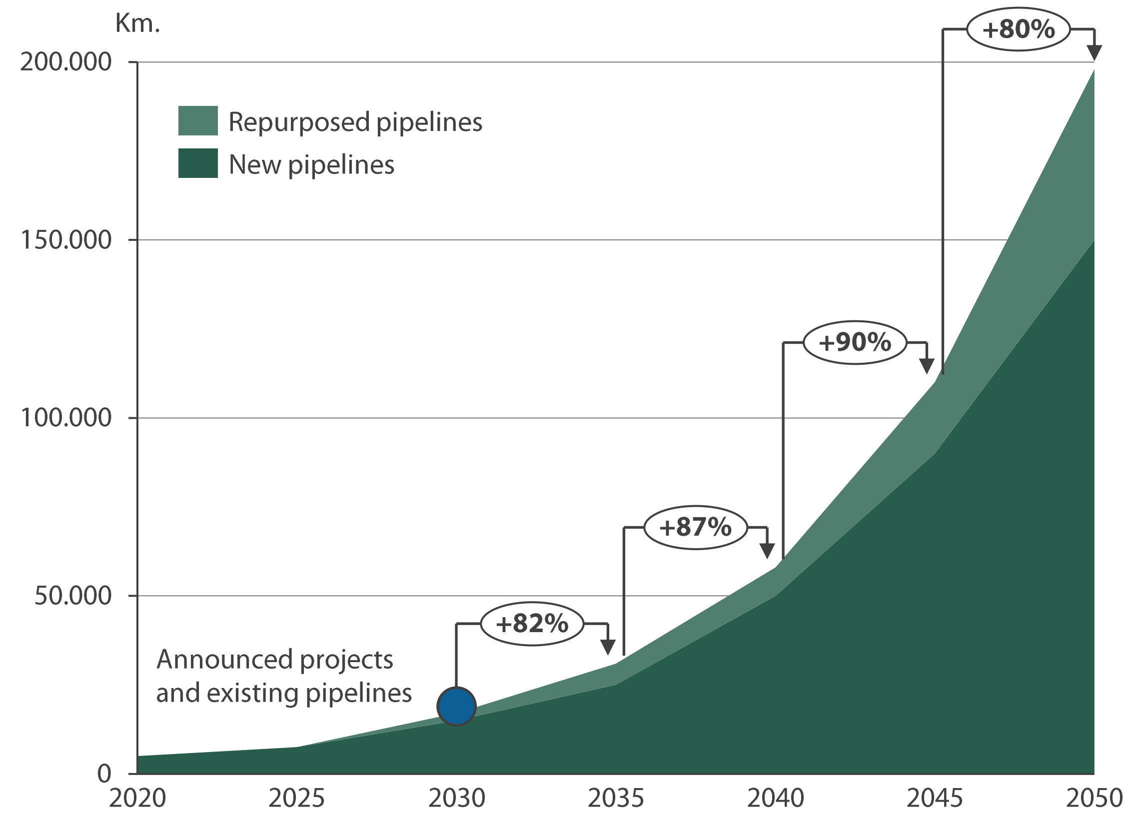


1) Energinet: Systemperspektivanalyse 2022

Content

60-80% of the European H2 infrastructure is forecasted to consist of repurposed NG pipelines

Established H2 infrastructure, global forecast[1]



Description

- As of 2022, around 5.000 kilometres of dedicated hydrogen pipeline are installed globally
- The International Energy Agency are forecasting a build-out of up to 200.000 kilometres of hydrogen pipeline by 2050
  - Whereof ~25-50% consist of repurposed natural gas pipelines[2]
  - >50.000 kilometres pipeline will be established in Europe[3]
    - 60% will be repurposed pipeline according to IEA
    - Up to 80% will be repurposed according to DNV
- In comparison there is currently installed +1.2 million kilometres of natural gas pipelines, with 200.000 kilometres of pipeline in development (mainly in Asia.)[4]

Key take out:

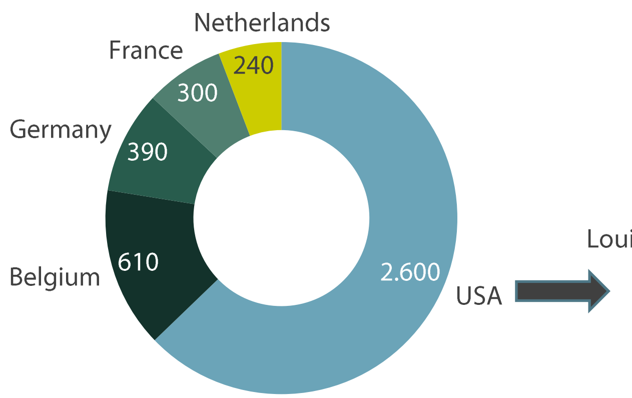
- 200.000 kilometres pipeline is forecasted globally by 2050
  - With +50.000 kilometres installed in Europe
  - Consisting of 60-80% repurposed NG pipelines by 2050
- Europe will have the highest share of repurposed NG pipelines among all regions
- In Denmark, the build-out of hydrogen pipelines will mainly consist of new pipes as existing NG pipelines are expected to be used for biogas

1) International Energy Agency – Energy Technology Perspectives 2023 2) DNV – Hydrogen Forecast 2022 3) European Hydrogen Backbone (2022) 4) Global Energy Monitor – Pipe Dreams 2022

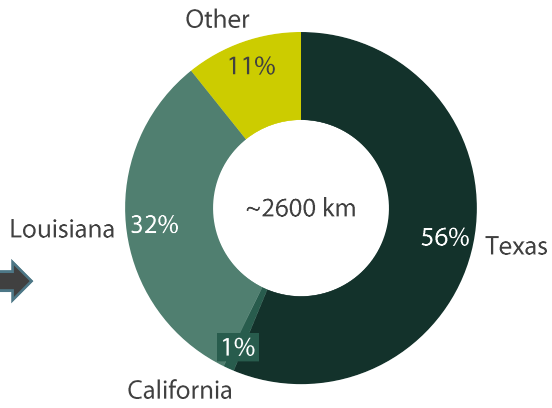
US have the most developed hydrogen pipeline infrastructure in the world - perfectly suited for supporting IRA fundings

Established H2 infrastructure

Top five countries with H2 pipelines (in km)[1]



Concentration of hydrogen pipeline in US[2]



- Due to their high capacity and economies of scale, pipelines are the most economic transportation mode for hydrogen over long distances in large quantities
- Nearly all hydrogen in the U.S. is transported using dedicated hydrogen pipeline infrastructure
- The U.S. has ~2,600 kilometres of hydrogen pipelines, the largest network in the world (Belgium ranked 2nd has +600 kilometres, Germany ranked 3rd ~390 kilometres)

Description

Outline, H2 Pipeline infrastructure in US Gulf coast

- Texas has over 1400 kilometres (>56%) and California 25 kilometres (<1%) of total U.S. hydrogen pipelines
- With the US experience in pipeline development, the market is well-suited for supporting the hydrogen escalation expected by the IRA funding program
- With approx. 40% of global Hydrogen networks located in Europe, a strong basis exists for further extending the infrastructure across key markets expecting a strong demand growth

1) Statista 2) Congressional Research Service (CRS)

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Exponential capacity growth when moving up in pipeline size, +20% CAPEX increase reduces lifetime transport cost by +40%

Summary: Pipeline costing

	Pipe size and distance	Capacity (GW)	CAPEX (bDKK)	OPEX (mDKK/y)	DKK/kg. H2[1]
	24″	2,1	1,3	28,8	0,15 (+77%)
Base case	36″ (ON)	5,6	1,9	42,4	0,08
Base case	36″ (OF)	5,6	2,8	62,2	0,12
	48″	11,5	2,3	51,1	0,05 (-42%)

Esbjerg → Fredericia

← 100 km →

ON | OF

1) Assumptions: lifetime: 40 years, pressure: 35/20 bar, capacity utilization: 75% 2) European Central Bank

Description

- Levelized transport costs decrease with increase in pipeline size and capacity
- Advantages with larger pipe sizes:
  - Significant decrease in levelized transport costs of up to ~70% from 24″ to 48″ pipes.
  - Increased capacity for line-packing.
  - Reduction in loss of energy = reduction in unitary compressor costs.

Key take out:

- 20% CAPEX increase will reduce hydrogen transport costs by +40% and enable future hydrogen investments
- Numbers are based on pre-global inflation disruption
  - Indications of ~70-80% increase in steel prices from 2020 to 2022[2]

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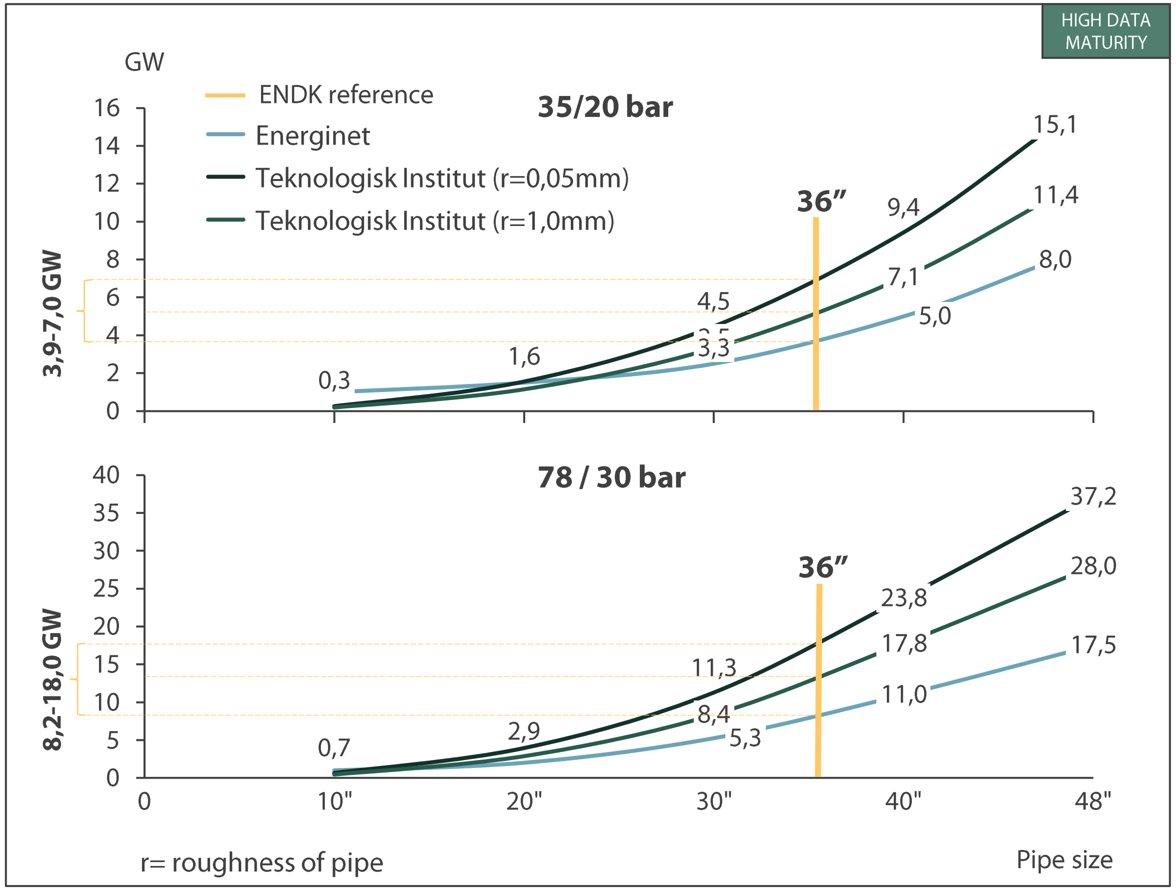
An increase in pipe size from 36” to 48” increases pipeline capacity with ~100%

Capacity vs. pipe size



Description

- Three scenarios are shown on each of the graphs on the left side containing three data sources:
  - Estimate from Energinet[1]
  - Estimate from DTI with pipe roughness of 0,05mm (extremely smooth surface)[2]
  - Estimate from DTI with pipe roughness of 1,00mm (extremely rough surface)
- The capacity for a 36” pipe (Energinet reference size) is estimated between 3,9 – 7,0 GW with a pipe pressure of 35/20 bar
- By increasing the pipe size from 36” to 48” the capacity increases to a range between 8,0 - 15,1 GW is reached
- If the pressure inside the pipe is increased to 78/30 bar the capacity increased further:
  - 36” pipe: 8,2 – 18,0 GW
  - 48” pipe: 17,5 – 37,2 GW

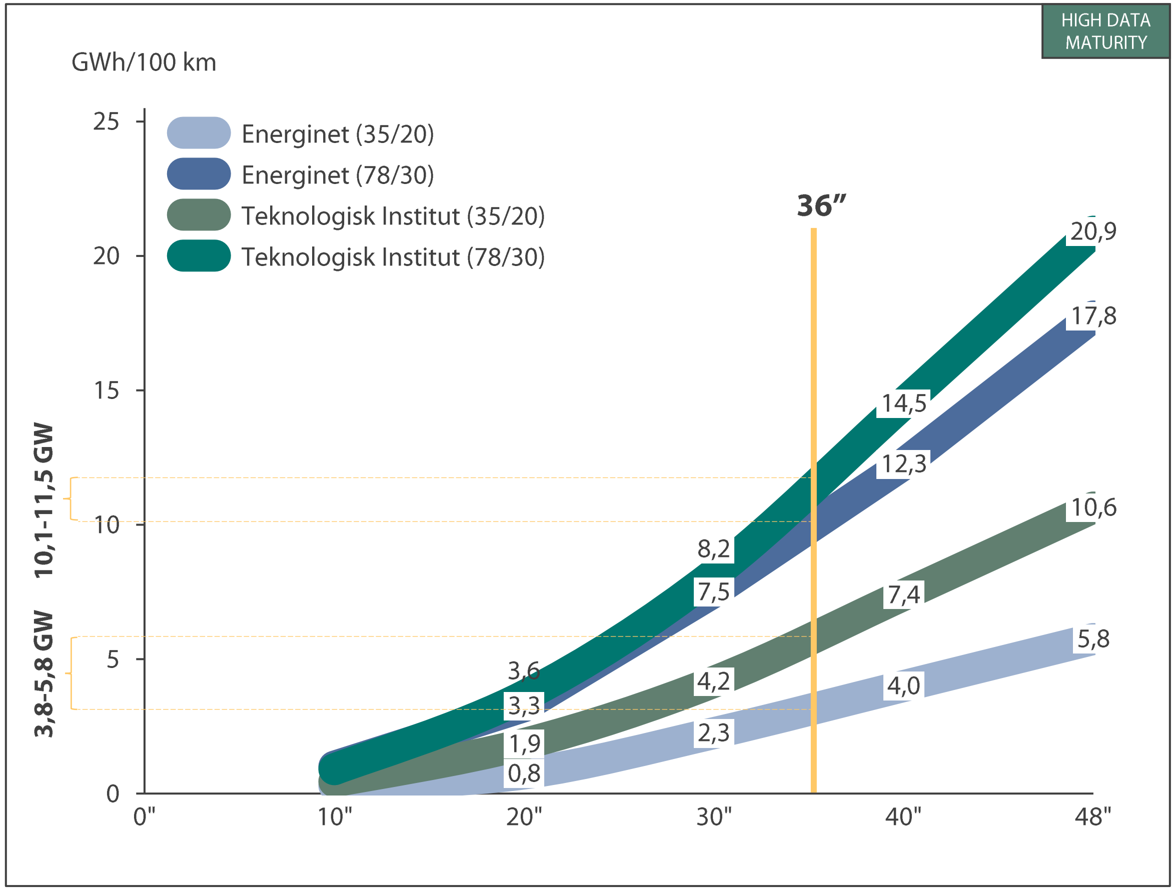
Key take out:

- The calculation and numbers behind the estimates from DTI are indicating rather conservative estimates from Energinet
- Based on assessment of data input, the capacity for a 36” pipeline is:
  - 35/20 bar: ~6,2 GW
  - 78/30 bar: ~15,8 GW
- Increase in pipe size is exponentially increasing capacity

1) Energinet: Systemperspektivanalyse 2022 **2)** Calculations done by Danish Technological Institute)

An increase in pipe size from 36” to 48” increase line-pack gain by ~80%

Line-packing vs. pipe size



Description

- Four scenarios are shown on the graph to the left side based on two data sources:
  - Energinet[1]
  - DTI[2]
- The line-packing potential for a 36” pipe (Energinet reference size) is estimated between 3,8 – 5,8 GWh/100 km with a pipe pressure of 35/20 bar
- By increasing the pipe size from 36” to 48” the line-packing potential increases to a range between 5,8 - 10,6 GWh/100 km is reached
- If the pressure inside the pipe is increased to 78/30 bar the line-packing potential increases further:
  - 36” pipe: 10,1 – 11,5 GWh / 100 km.
  - 48” pipe: 17,8 – 20,9 GWh / 100 km.

Key take out:

- The calculation and numbers behind the estimates from DTI are indicating rather conservative estimates from Energinet:
- Based on assessment of data input, the line-packing potential for a 36” pipeline is:
  - 35/20 bar: ~5,8 GWh / 100 km. (around 7,5 GW electrolyser production)
  - 78/30 bar: ~11,5 GWh / 100 km. (around 14,5 GW electrolyser production)
- Increase in pipe size is exponentially increasing line-packing possibilities

1) Energinet: Systemperspektivanalyse 2022 **2)** Calculations done by Danish Technological Institute

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