Institute of Energy Economics
at the University of Cologne

EWI research report

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Low-Carbon Hydrogen

A techno-economic and regulatory analysis

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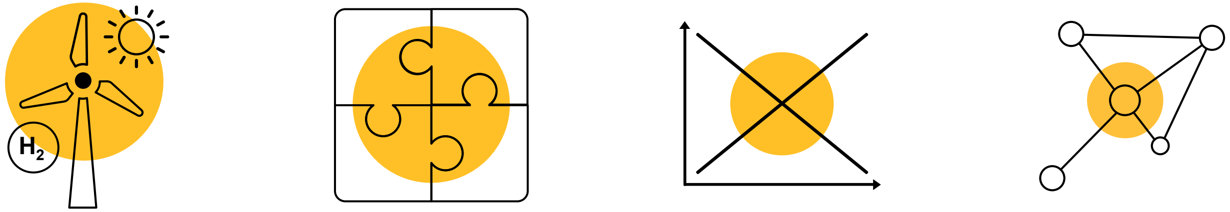

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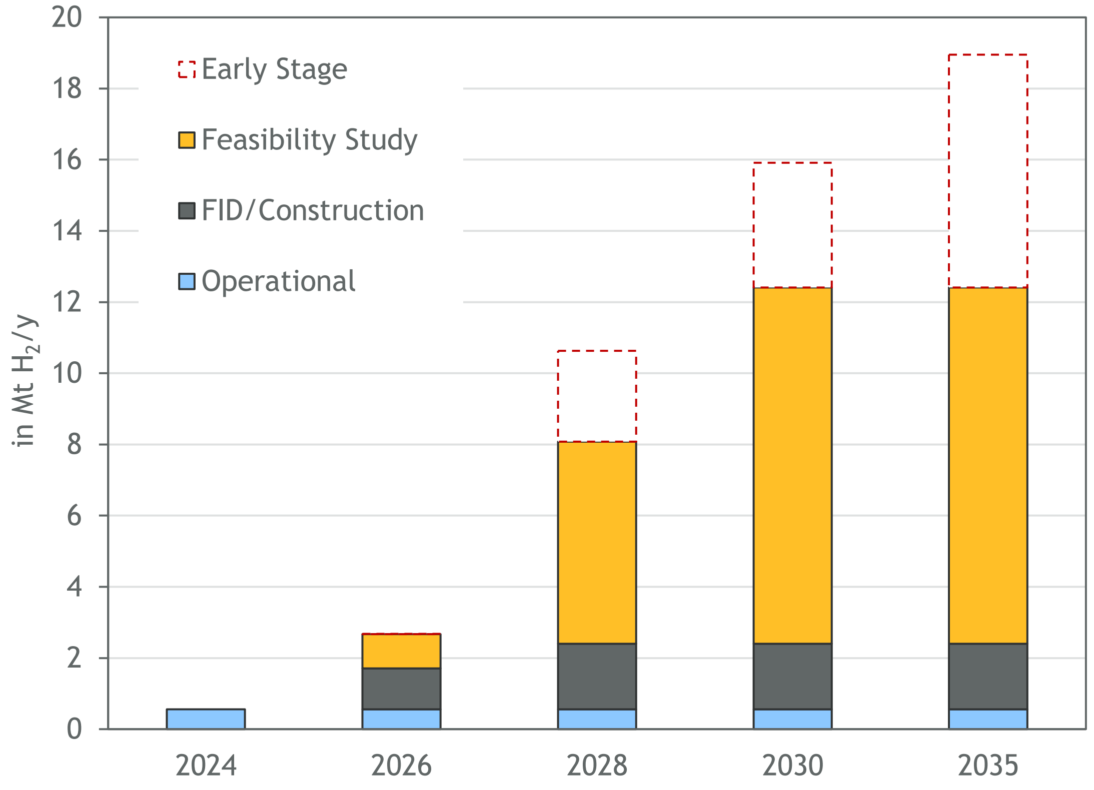
Low-carbon hydrogen from natural gas with carbon capture and storage faces challenges regarding CO_2 infrastructure and regulation

Motivation

- In order to reach the EU's ambitious climate targets, hydrogen will become a valuable energy carrier for the energy transition. It can be produced with various technologies, among them electrolysis and renewable electricity (green hydrogen) and natural gas reforming with carbon capture and storage, which will be referred to as low-carbon hydrogen in this report.
- Low-carbon hydrogen is considered a bridging technology by stakeholders to support a rapid hydrogen market ramp-up. The draft of an EU Delegated Act defines an emission reduction target for low-carbon hydrogen of 70 % compared to the emissions associated with natural gas.
- While the production capacity of operational low-carbon hydrogen projects is low as of today, a lot of projects worldwide are currently evaluated in a feasibility study or in early stage. Until 2030, up to 16 Mt/y (533 TWh) of low-carbon hydrogen could be produced globally, according to the current pipeline of projects[1].
- However, the production of low-carbon hydrogen poses challenges in CO_2 transport and long-term storage, infrastructure ramp-up and coordination of stakeholders. This analysis focuses on the techno-economic and regulatory aspects of low-carbon hydrogen to contribute a scientific viewpoint to the current discussion.

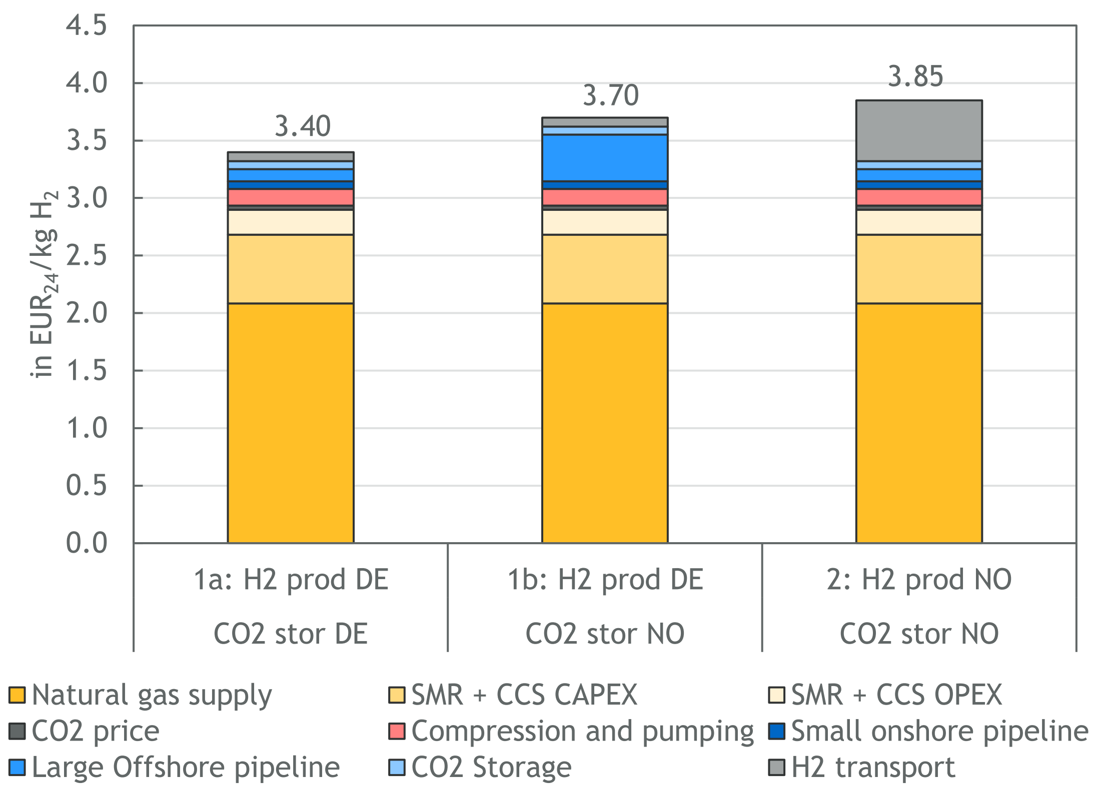
Existing and announced low-carbon hydrogen production projects, global[1]



1: IEA (2024) Hydrogen Production and Infrastructure Projects Database, includes only projects with information on commissioning year.

Supply costs of low-carbon hydrogen could be lower for production in Germany than in Norway, including H_2- and CO_2-transport

Supply costs of low-carbon hydrogen[1]



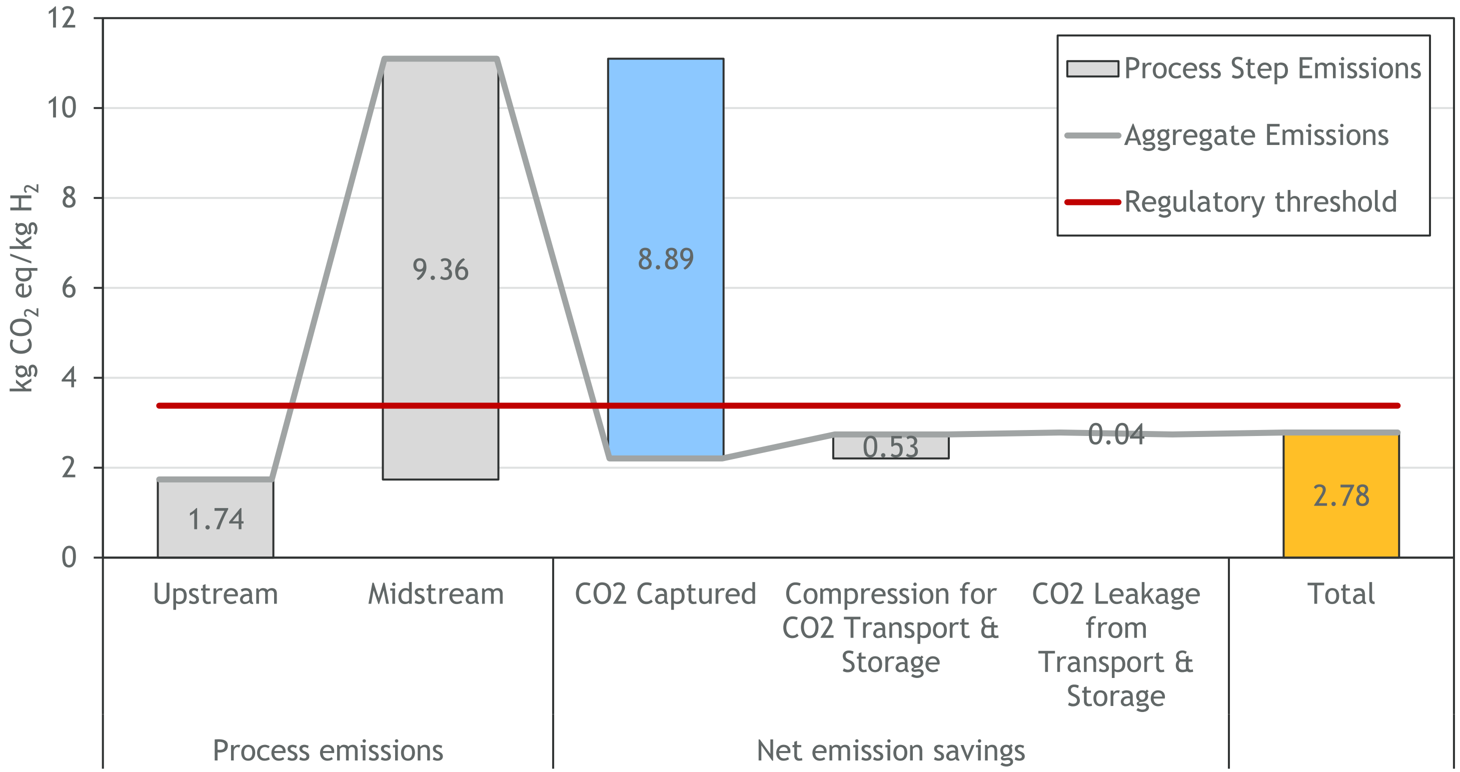
Key insights

- Production costs for low-carbon hydrogen from natural gas with carbon capture and storage could range between 3 and 4 EUR/kg under the given assumptions in this analysis (i.e., CO_2 capture rate = 95 %, natural gas price = 45 EUR/MWh, further assumptions[2]).
- The main cost drivers for low-carbon hydrogen production are variable OPEX costs for natural gas supply rather than CAPEX costs for the production process.
- Transportation of CO_2 via pipeline over long distances may be cheaper than transportation of hydrogen. Therefore, for low-carbon hydrogen consumption in Germany, production costs for production in Germany could be cheaper than for production in Norway, even if the CO_2 is transported back to Norway.
- There are uncertainties regarding the costs for CO_2 capturing, transportation and storage, which could affect the actual range of supply costs. Geological conditions, scaling effects, and monitoring requirements additionally influence CO_2 storage costs.

1: EWI analysis | 2: Assumptions: natural gas price: 45 EUR/MWh, other cost assumptions in chapter 3. Transport distances: scenario 1a: H_2: 300 km onshore, CO_2: 300 km offshore; scenario 1b: H_2: 300 km onshore, CO_2: 1000 km offshore; H_2: 1000 km offshore and 300 km onshore, CO_2: 300 km offshore.

Low-carbon hydrogen production must achieve a CO_2 capture rate of at least 88 % to comply with EU regulation

Emissions from low-carbon hydrogen (incl. subsequent CO_2 transport and storage)[1]



1: Own calculation based on the methodology presented in chapter 4.

Key insights

- The diagram illustrates CO_2 emissions from low-carbon hydrogen production (natural gas + CCS), including CO_2 emissions from compression for transport, storage and leakage.
- Under the assumed parameters, mainly a CO_2 capture rate of 95 %, hydrogen production from natural gas meets the regulatory threshold of ~3.4 kg CO_2 eq./kg H_2 specified by the drafted EU regulatory framework.
- Conversely, for the given parameterization, the capture rate would have to be at least 88 % to meet the threshold. Lower capture rates increase uncaptured process emissions.
- Nonetheless, emissions of ~2.8 kg CO_2 eq./kg H_2 remain, hence, low-carbon hydrogen is not climate neutral.

Regulatory framework for low-carbon hydrogen will be defined on EU level, legal framework of CO_2 transport and storage pending

		Legal framework	Regulatory framework	Policy targets	Market incentives (incl. funding)
Low-carbon H_2	Production & Import		▪ Announced: Delegated act for low-carbon fuels (70 % GHG emission reduction along entire value chain) ▪ Effective: EU taxonomy (73.4 % GHG emission reduction along entire value chain)	▪ No specific policy targets in REPowerEU and European hydrogen strategy ▪ No specific policy targets in Updated National hydrogen strategy and Hydrogen import strategy	▪ Eligible for funding, e.g. IPCEI status ▪ Potential access to funding programs through compliance with EU taxonomy
	Transport & Storage	▪ Approved: National hydrogen core network (EnWG §112b)		▪ Announced: European hydrogen backbone (private initiative, not binding) ▪ Announced: National storage strategy	▪ Approved: mechanism for inter-temporal allocation of hydrogen network costs
	End use	▪ Heating sector: applicable for Building Energy Act targets (GEG §71f)		▪ Not applicable for RED III quotas for RFNBOs ▪ Power plant strategy	▪ CO_2 prices of EU ETS1 and ETS2 ▪ Applicable for Carbon Contracts for Differences
CO_2	Transport	▪ Announced: amendment to KdSpG	▪ Emissions are balanced according to Delegated act for low-carbon fuels and EU taxonomy ▪ EU net-zero industry act	▪ Approved: EU net-zero industry act	▪ Eligible for funding, e.g. PCI/PMI status
	Storage	▪ Large-scale CO_2 storage currently not permitted ▪ Announced: amendment to KdSpG	▪ Emissions are balanced according to Delegated act for low-carbon fuels and EU taxonomy	▪ Approved: EU net-zero industry act	▪ Eligible for funding, e.g. PCI/PMI status

Color coding: EU level, National level (Germany)

Low-carbon hydrogen production might be scaled up quickly, but challenges remain regarding infrastructure and regulation

Low-carbon hydrogen production:

- Low-carbon hydrogen production (here: steam methane reforming with CCS) is a process with a high technology readiness level which could be scaled up for large production volumes in the short-term. It is, however, not climate neutral as residual CO_2 emissions remain.
- Although low-carbon hydrogen might be believed to play a bridging role in the market ramp-up, there are no explicit policy production targets on EU level and in Germany.

Legal and regulatory framework:

- The drafted Delegated Act on low-carbon hydrogen has yet to be adopted and transposed into national law.
- Uncertainties in the regulation of the low-carbon hydrogen value chain lead to investment risk.
- For a market scale-up of projects with FID status, stakeholders need clarity on the envisaged role of low-carbon hydrogen and potential policy support.

Infrastructure:

- For transport and storage of low-carbon hydrogen, the same infrastructure is required as for green hydrogen, and it is thus dependent on its timely ramp-up.
- Additionally, CO_2 has to be transported and stored. The legal and regulatory framework for CO_2 infrastructure is less developed than for hydrogen infrastructure. CO_2 storage is currently prohibited in Germany, as is the CO_2 export for offshore storage.

Market incentives:

- Low-carbon hydrogen can contribute to lower emissions and reach emission reduction targets in all sectors.
- While OPEX costs are driving total supply costs rather than CAPEX, investment funding may not be fruitful.
- EU funding schemes like PCI and IPCEI generally support projects for low-carbon hydrogen and CO_2 infrastructure.

1. Introduction

- Definition of low-carbon hydrogen
- The role of low-carbon hydrogen in German, European and global climate neutrality studies

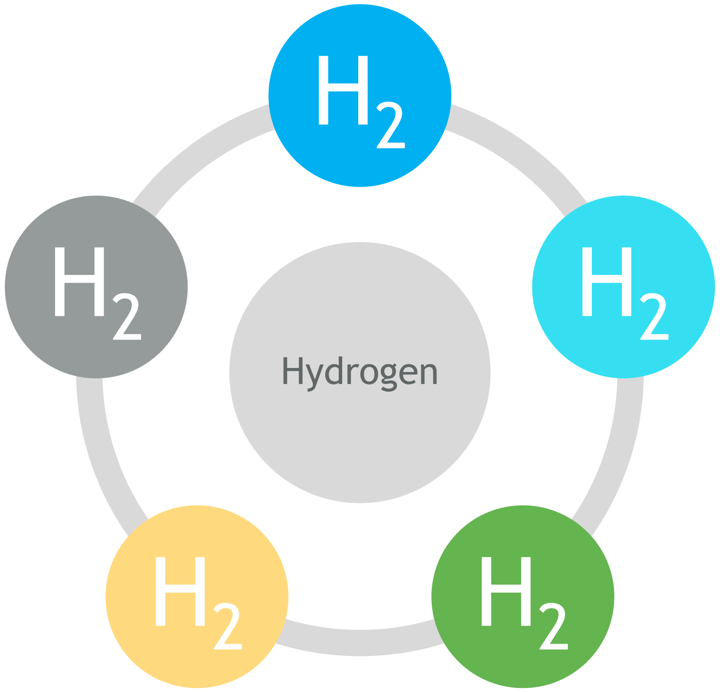
The colors of hydrogen

Low-carbon hydrogen mostly refers to blue hydrogen made from natural gas with CCS

Motivation

- Hydrogen is a promising energy carrier for the energy transition. It burns carbon-free and offers one, or in some applications the only, currently viable decarbonization option.
- Hydrogen can be produced from a variety of sources. The most sustainable source is production from water electrolysis using renewable electricity. Currently, discussions are arising whether green hydrogen will be available in time and in sufficient quantities to reach emission reduction targets.
- For this reason, stakeholder's attention on low-carbon hydrogen from other energy sources than renewables is rising. The EU currently consults on a Delegated Act on low-carbon hydrogen, which entails e.g. the methodology for calculating emission savings.

Colors of hydrogen



Renewable hydrogen

- **Green**: Electrolysis powered by renewable energy sources (RES)

Low-carbon hydrogen[1]

- **Blue**: Produced from fossil fuels, with Carbon Capture and Storage (CCS)
- **Turquoise**: Pyrolysis of fossil fuels
- **Yellow**: Electrolysis powered by nuclear energy

Carbon-intensive hydrogen

- **Grey:** Produced from fossil fuels (coal or natural gas), without Carbon Capture and Storage (CCS)

1: This research report focuses mainly on blue hydrogen (from natural gas with carbon capture and storage), which will hereinafter be referred to as „low-carbon hydrogen".

Low-carbon hydrogen

Production process and environmental impact of low-carbon hydrogen

Production process

- Low-carbon hydrogen refers to hydrogen produced from non-renewable sources. For this research report, the focus is set on low-carbon hydrogen produced through a process called **natural gas reforming** (e.g., steam methane reforming or autothermal reforming), which converts methane (CH_4) into hydrogen (H_2) and carbon dioxide (CO_2).
- Methane reacts with steam to produce hydrogen and CO_2. The resulting CO_2 is **captured and stored (CCS)**.
- Steam reforming is expressed by:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

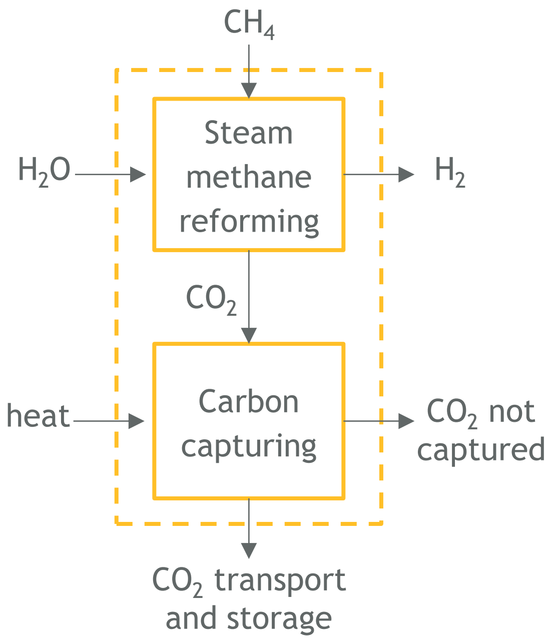
- Additional hydrogen can be obtained through the subsequent water-gas shift reaction:

$$CO + H_2O \rightarrow CO_2 + H_2$$

The environmental impact

- **Capture:** CO_2 emissions are captured during the natural gas reforming process.
- **Transport:** Captured CO_2 is then compressed and transported, mostly via pipelines, ships, or trucks, to storage sites.
- **Storage:** CO_2 is injected into underground geological formations, where it is stored to prevent its release into the atmosphere[2].
- Compared to grey hydrogen, low-carbon hydrogen is associated with lower emissions along its value chain, but the emissions are not eliminated.
- Because of e.g. upstream methane leakage, imperfect capture rates and CO_2 leakage, low-carbon hydrogen cannot be considered climate neutral.

Simplified process illustration[1]



1: Own illustration of low-carbon hydrogen production via steam methane reforming (SMR). | 2: Hydrogen from SMR is not considered low-carbon hydrogen if the CO_2 is used (CCU) rather than stored (CCS).

The role of low-carbon hydrogen in recent literature: Germany

„Big 5“ climate neutrality studies show limited use of low-carbon hydrogen, if any

- The "Big 5" German climate neutrality studies of 2021 differentiate between domestic production of hydrogen and imports. Domestic production in the scenarios is based exclusively on water electrolysis (green hydrogen). Low-carbon hydrogen production in Germany does not take place in any scenario. This is based on and compliant with the legislation and political communication at the time of the Big 5, as the production of low-carbon hydrogen was legally prohibited in Germany at that time.
- However, in the Ariadne scenarios, grey hydrogen production on a fossil basis (SMR without CCS) takes place at times when water electrolysis cannot meet demand. In a second Ariadne scenario, biogenic hydrogen production is considered.
- Low-carbon hydrogen is considered an option in the form of imports in the studies. However, the Big 5 scenarios do not specify the production route. Dena pilot study (DLS2) is an exception. In this study, around 5 TWh of low-carbon hydrogen is imported from abroad in 2030. The other studies only scarcely mention the possibility and relevance of importing blue hydrogen to cover domestic demand.

		DLS2[1]	Agora[2]	LFS[3]	BDI[4]	Ariadne[5]
Production	Explicit domestic production of low-carbon H_2	x	x	x	x	x
	Explicit domestic production grey H_2	x	x	x	x	✓
	Explicit exclusion of domestic production of low-carbon H_2	✓	x	x	x	(✓)
Import	Explicit import of low-carbon H_2	✓	✓	x	x	x
	Explicit exclusion of import of low-carbon H_2	x	x	x	x	x
Use	Explicit use of low-carbon H_2	✓	x	x	x	x
	Explicit exclusion of use of low-carbon H_2	x	x	x	x	(x)

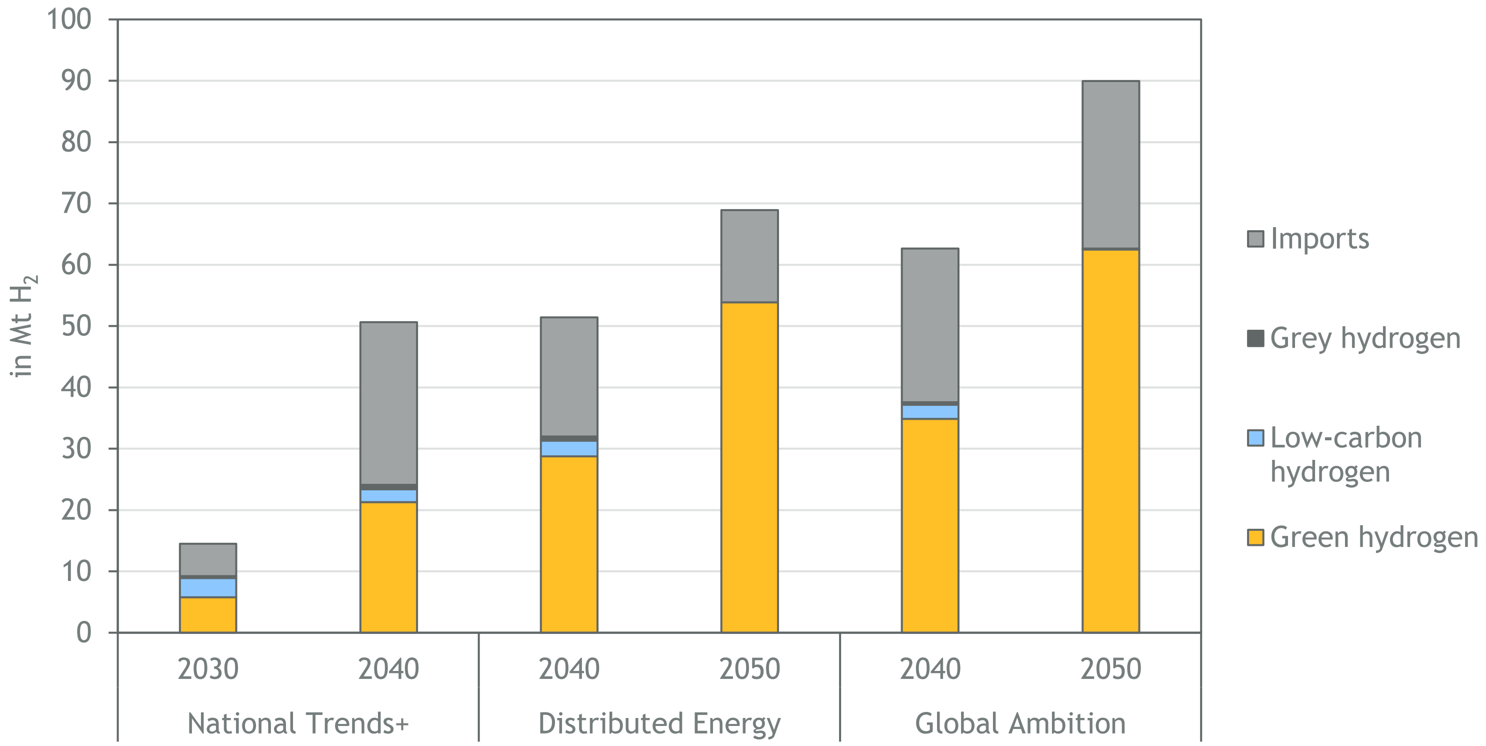
Note: The table is created on the basis of remarks in the studies. No explicit exclusion does not imply explicit production / import / use.

1: EWI (2021) Dena Pilot Study - Towards Climate Neutrality | 2: Agora (2021) Klimaneutrales Deutschland | 3: Fraunhofer et al. (2021) Long-term Scenarios for the Transformation of the Energy System in Germany | 4: BCG (2021) Climate Paths 2.0 | 5: PIK et al. (2021) Deutschland auf dem Weg zur Klimaneutalität 2045

The role of low-carbon hydrogen in recent literature: EU

TYNDP 2024 suggests diminishing shares of low-carbon hydrogen over time

Hydrogen total energy demand in the EU according to TYNDP 2024[1] [Mt]



1: Own calculation based on TYNDP (2024) Scenarios Report

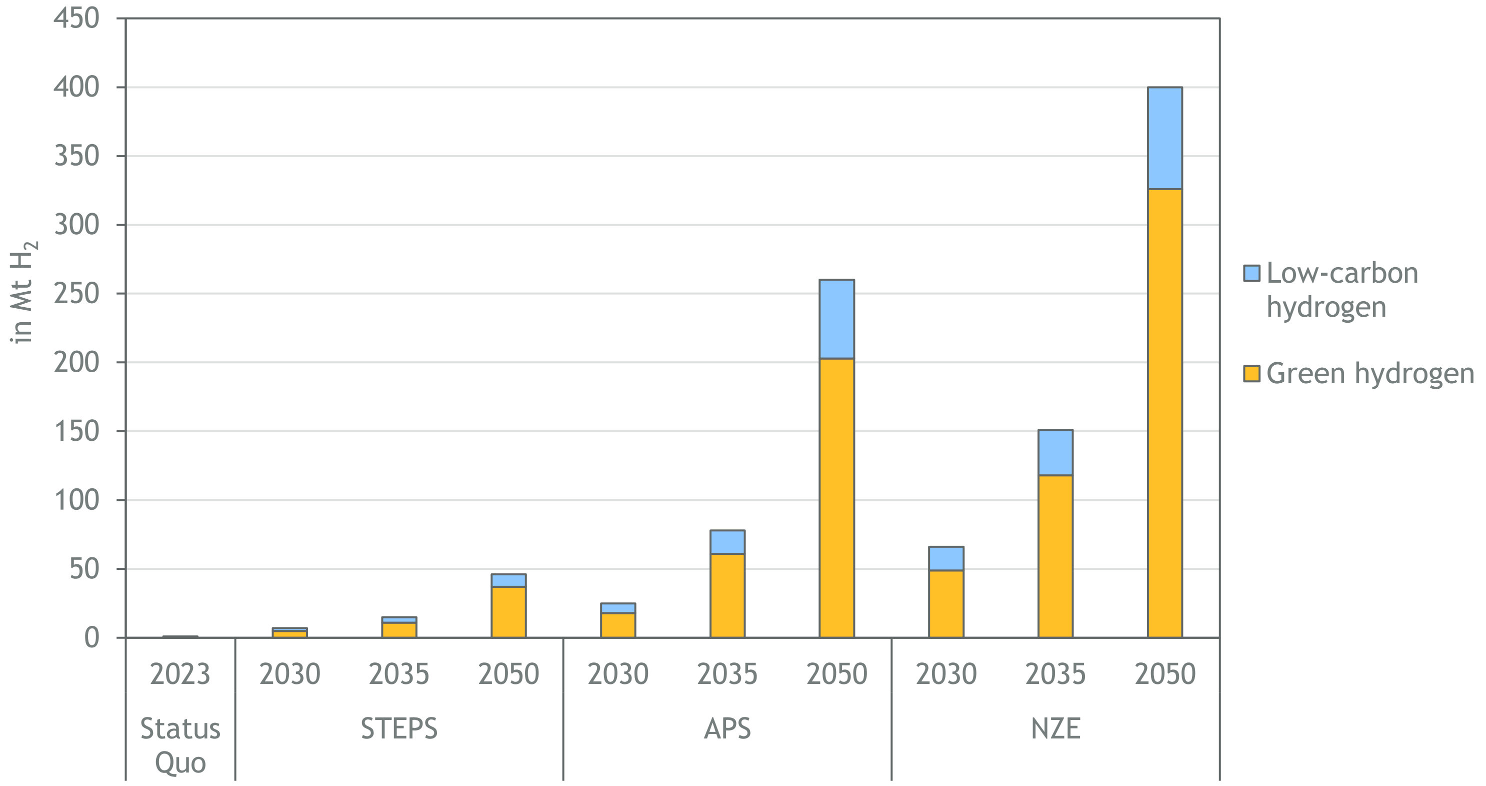
The Ten-Year Network Development Plan (TYNDP)

- The TYNDP of ENTSO-E and ENTSOG was initiated for the assessment of transmission infrastructure projects based on demand scenarios.
- According to the TYNDP 2024, in 2030, low-carbon hydrogen could account for over 22 % of all hydrogen demand in the EU, summing up to 3.15 Mt (~105 TWh) per year. This share decreases to roughly 4 % by 2040, which would amount to 2-2.5 Mt (~70-85 TWh) per year.
- Low-carbon hydrogen is expected to play only a minor role in 2050, covering 0.15 Mt per year of hydrogen demand in the Global Ambition scenario (<1 % of total hydrogen demand).
- A large and increasing share of hydrogen demand is expected to be covered by imports, which are not specified further regarding the production process.

The role of low-carbon hydrogen in recent literature: Global

World Energy Outlook 2024 suggests significant shares of low-carbon hydrogen

Global hydrogen production according to the World Energy Outlook 2024[1] [Mt]



1: Own illustration based on IEA (2024) World Energy Outlook 2024

Summary

- Globally, low-carbon hydrogen production in 2023 was below 1 Mt of hydrogen, according to the World Energy Outlook (WEO) 2024.
- Based on the WEO 2024, low-carbon hydrogen could account for over 25 % of total hydrogen production globally by 2030 and over 20 % by 2050 in the Announced Pledges (APS) and Net-Zero Emissions (NZE) scenarios.
- This amounts to up to 74 Mt (~2,500 TWh) of low-carbon hydrogen production in 2050 in the NZE scenario.
- This differs from the EU’s climate neutrality scenarios, where low-carbon hydrogen production declines as green hydrogen production increases. Future production depends mostly on costs and demand as well as the regulatory framework.

2. The current project landscape

- Status Quo: low-carbon hydrogen production projects globally by status, product, technology and end use
- Project Spotlights: Wilhelmshaven Energy Hub BlueHyNow & H2GE Rostock

Low-carbon hydrogen projects

A closer look at the project landscape reveals high production volume potential

Announced low-carbon hydrogen projects

- The production of grey hydrogen with a natural gas reforming process has been commercially operational for many years. Grey hydrogen is mostly used as feedstock in various industry processes like ammonia and methanol production. Next to natural gas, coal or oil can also be used as a feedstock for the reforming process. The addition of a carbon capture process to the natural gas reforming process can allow for the production of low-carbon hydrogen.
- The Hydrogen Production and Infrastructure Project Database by the International Energy Agency[1] not only records green hydrogen production projects, but also low-carbon hydrogen production projects.
- With regard to a possible ramp-up of the low-carbon hydrogen market, it is of interest where and how many production sites are planned.
- The following chapter provides an overview of the low-carbon hydrogen project landscape. For this purpose, the IEA database[1] is evaluated and illustrated according to the criteria listed on the right.
- In addition to the quantity dimension, the individual project idea is also of interest. To complement the worldwide project landscape overview, two projects in Germany are examined in more detail.

Differentiating features in the IEA Database[1,2]

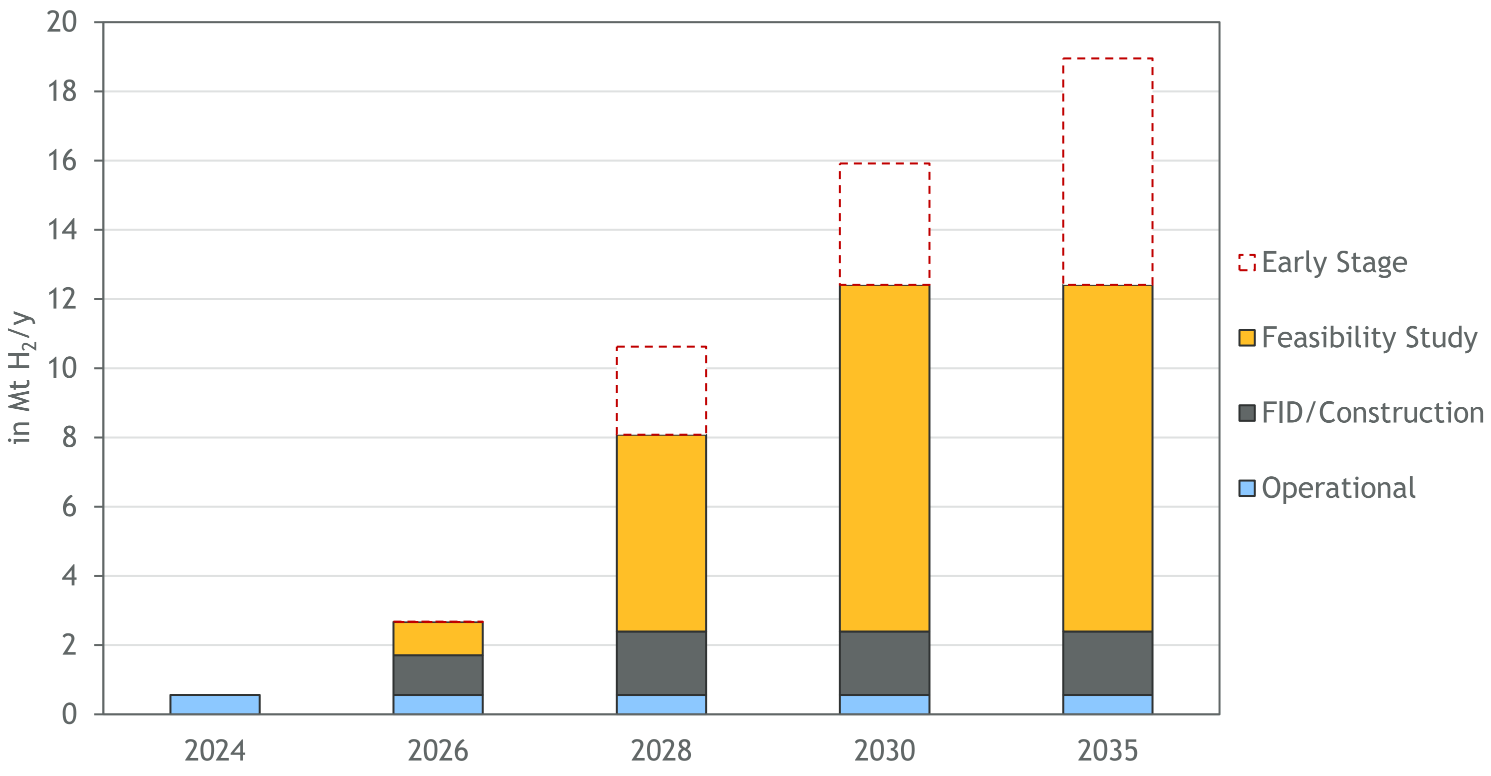
General information			
Geographical location	Capacity		
Status			
Operational	FID / under construction	planned	
Product			
Hydrogen	Ammonia	Methanol	
Feedstock			
Natural gas	Coal	Oil	
End-use sectors			
Refining and (petro-) chemicals	Industrials	Energy and heat supply	Mobility
Additional information[3]			
CO_2 capture rate	CO_2 sink		

1: IEA (2024) Hydrogen Production and Infrastructure Projects Database | 2: Only projects with an announced production capacity are evaluated hereinafter | 3: information often not available in the database

Global production of low-carbon hydrogen

Low volumes of operational and FID projects, high potential in planned projects

Existing and announced low-carbon hydrogen production projects, 2018-2035[1]



Summary

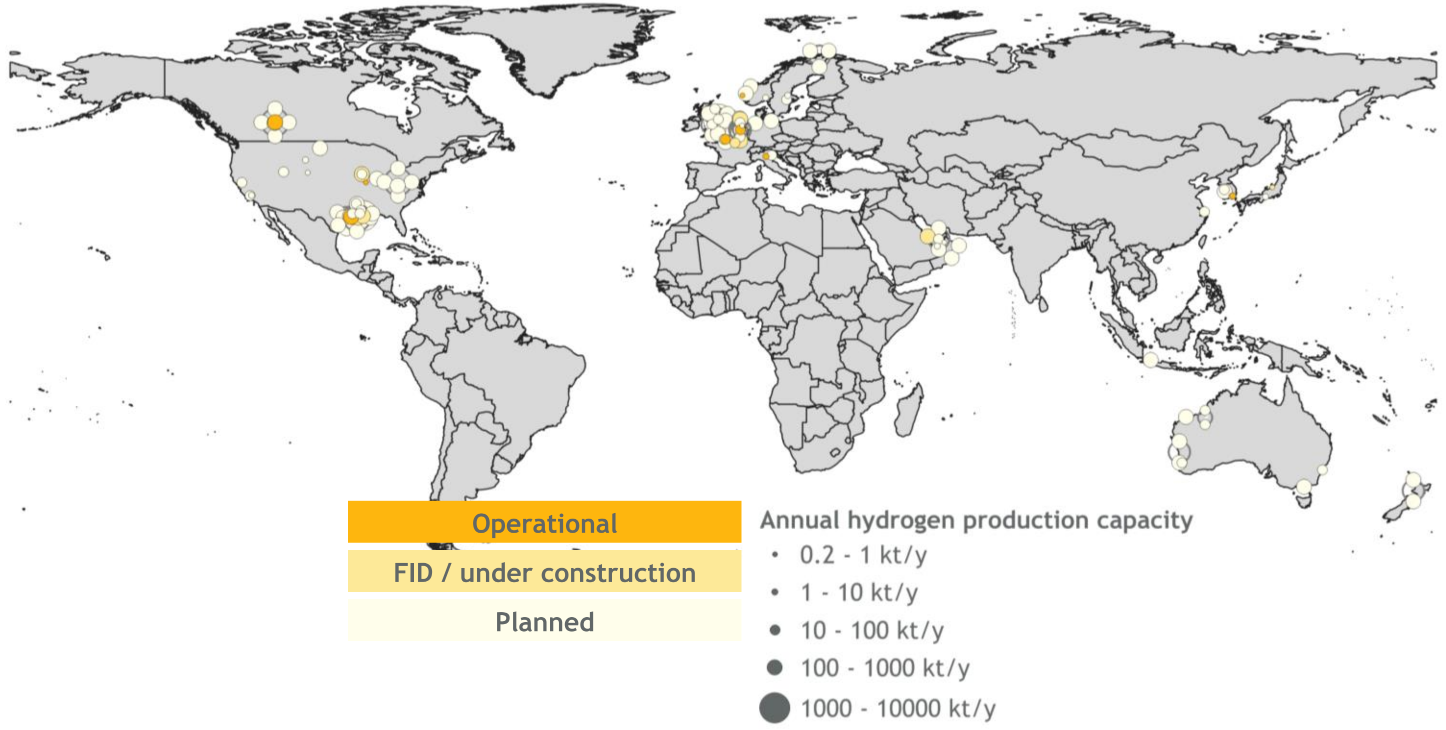
- As of 2024, the global production capacity for hydrogen from fossil fuels with CCUS[2] in operation amounts to 0.56 Mt/y (~18.7 TWh)
- By 2030, further projects with an additional capacity of
  - 1.84 Mt/y are currently in the FID stage or under construction,
  - 10.01 Mt/y are being evaluated in a feasibility study, and
  - 3.51 Mt/y are in early stage planning.
- If all these projects were realized by 2030, the total capacity of 16 Mt/y would be slightly lower than the low-carbon hydrogen production needed according to the 2030 Net-zero emissions scenario (NZE) of the World Energy Outlook 2024 (17 Mt/y).

1: IEA (2024) Hydrogen Production and Infrastructure Projects Database, includes only projects with information on commissioning year. | 2: Carbon Capture & Usage / Storage

Status: Low-carbon hydrogen production projects

Few projects are operational worldwide, many more are planned

World Map[1]



Explanation

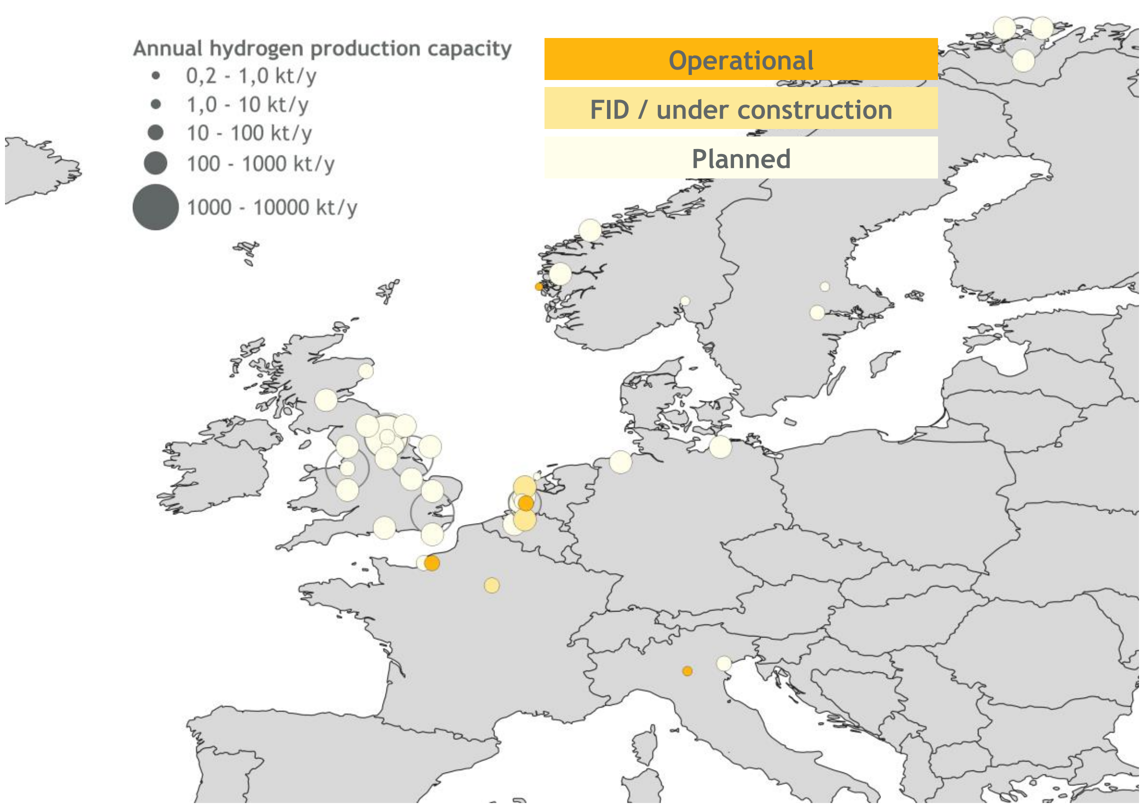
- According to the IEA database, there are currently around 167 projects (excluding demo projects) worldwide underway for the fossil-based production of hydrogen combined with CO_2 capture, of which
  - 20 are operational,
  - 16 with FID status or in construction,
  - 131 projects in early stage planning.
- Operational projects are located in North America (75 %) and Europe (25 %), while future projects are also announced in the Arabian Peninsula, Australia and Asia.
- Operational projects have an average capacity of 28 kt/y, while planned projects show a significantly higher average capacity of 144 kt/y.

1: Own illustration based on IEA (2024) Hydrogen Production and Infrastructure Projects Database

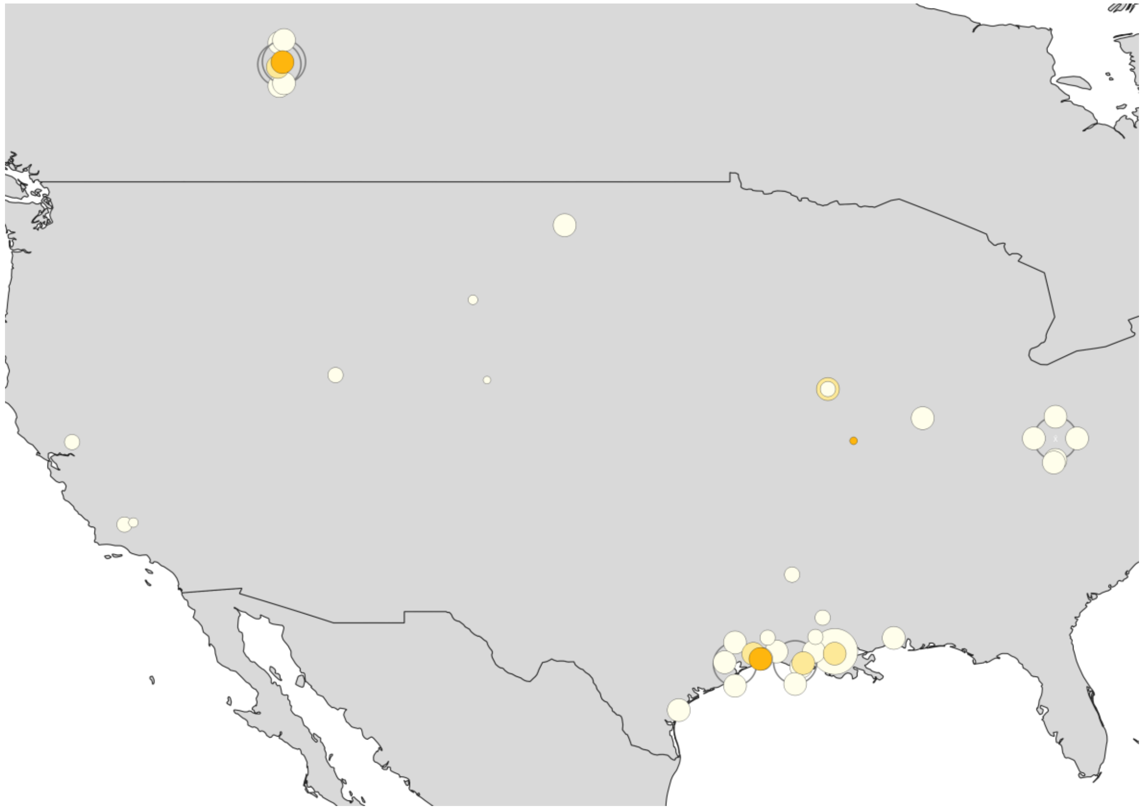
Status: Low-carbon hydrogen production projects

A closer look at Europe and North America

Europe[1]



North America[1]

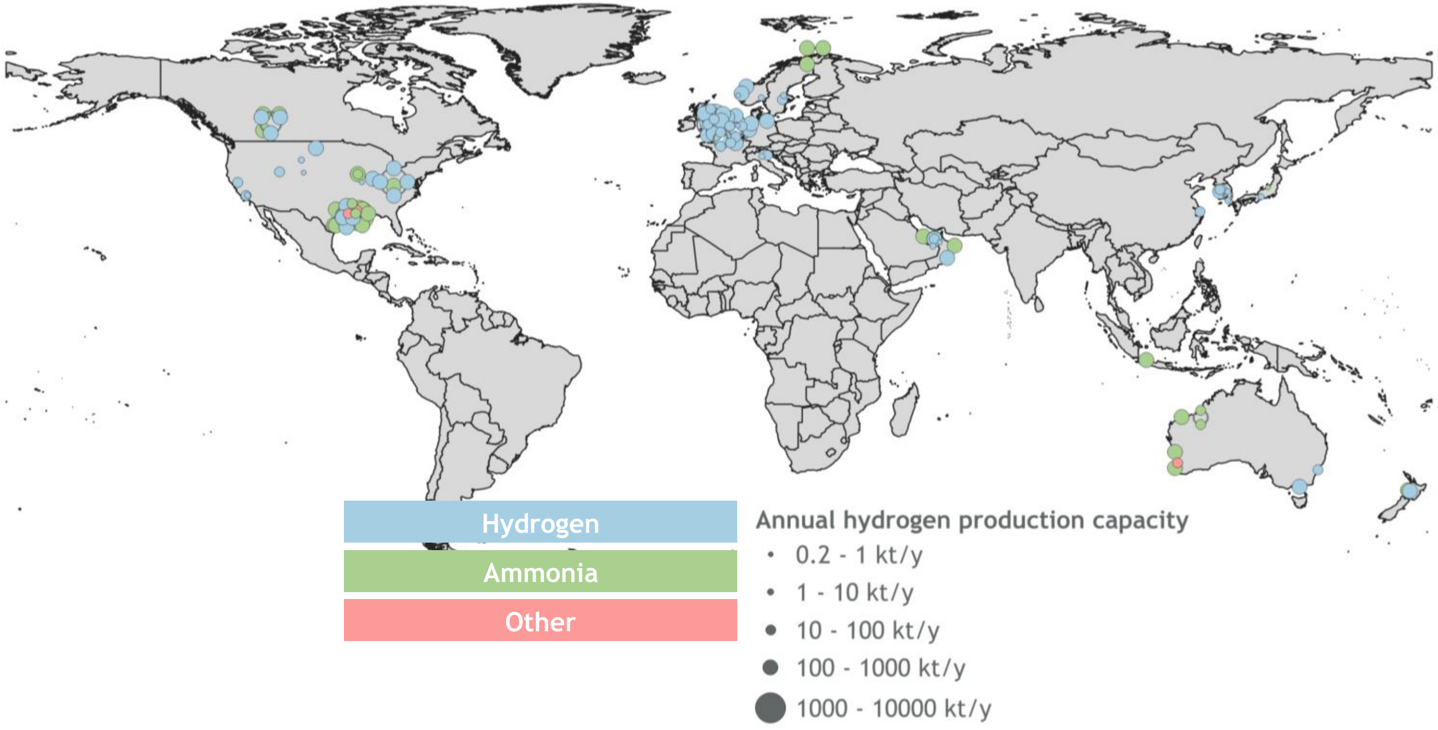


1: Own illustration based on IEA (2024) Hydrogen Production and Infrastructure Projects Database

Product: Low-carbon hydrogen production projects

The product in most projects is hydrogen, followed by ammonia

World Map[1]



1: Own illustration based on IEA (2024) Hydrogen Production and Infrastructure Projects Database

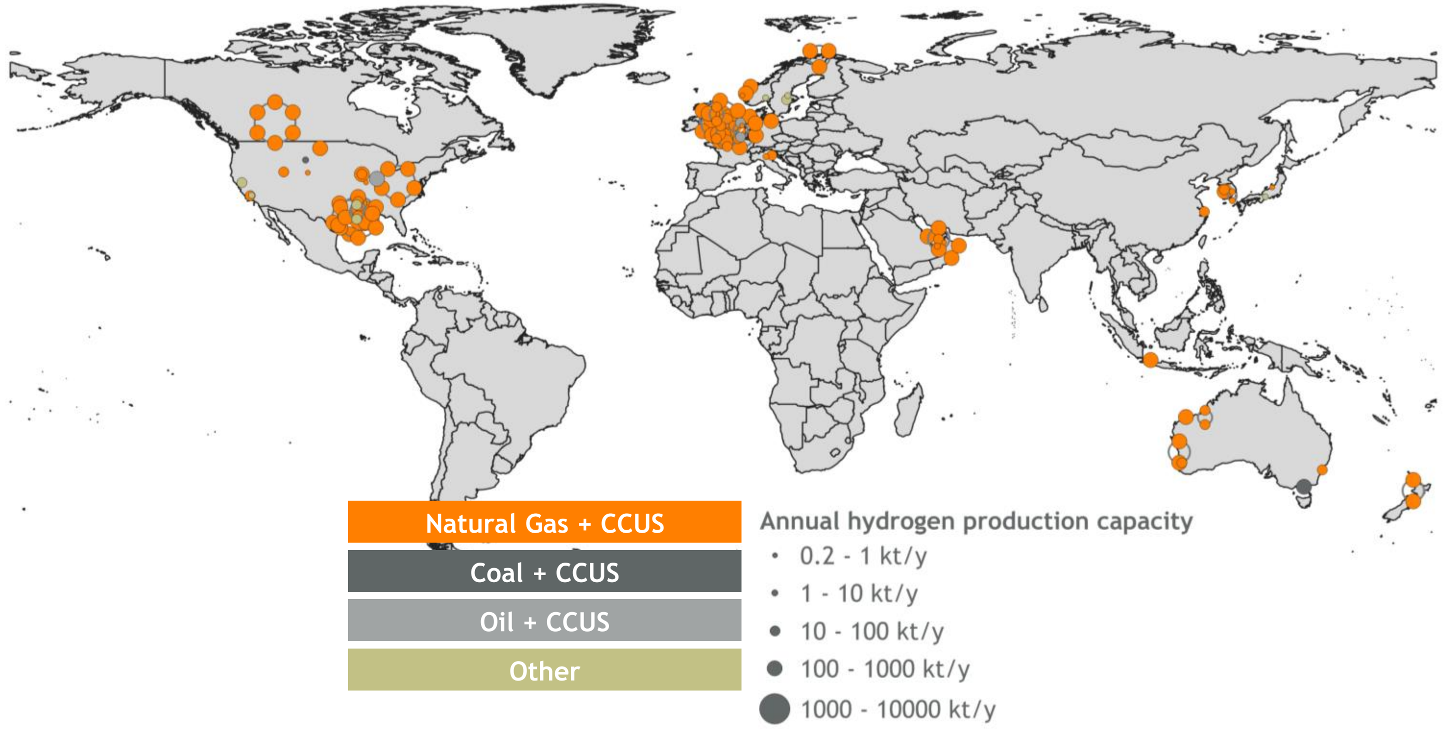
Explanation

- Low-carbon hydrogen can be used directly or in the form of a derivative.
- In the chemical industry, ammonia and methanol are important intermediate products that require hydrogen as a feedstock.
- In addition to the production of hydrogen, some of the projects also envisage its subsequent use in the form of a derivative.
- According to the database, 36 % of total capacity in the projects is designated for further processing as a derivative.
- The data shows that the use of hydrogen in ammonia synthesis dominates the subsequent use in derivatives (90 %).
- In Europe, hydrogen projects without a designated subsequent use dominate (94 %).

Technology: Low-carbon hydrogen production projects

Steam methane reforming of natural gas with CCUS dominates the project landscape

World Map[1]



Explanation

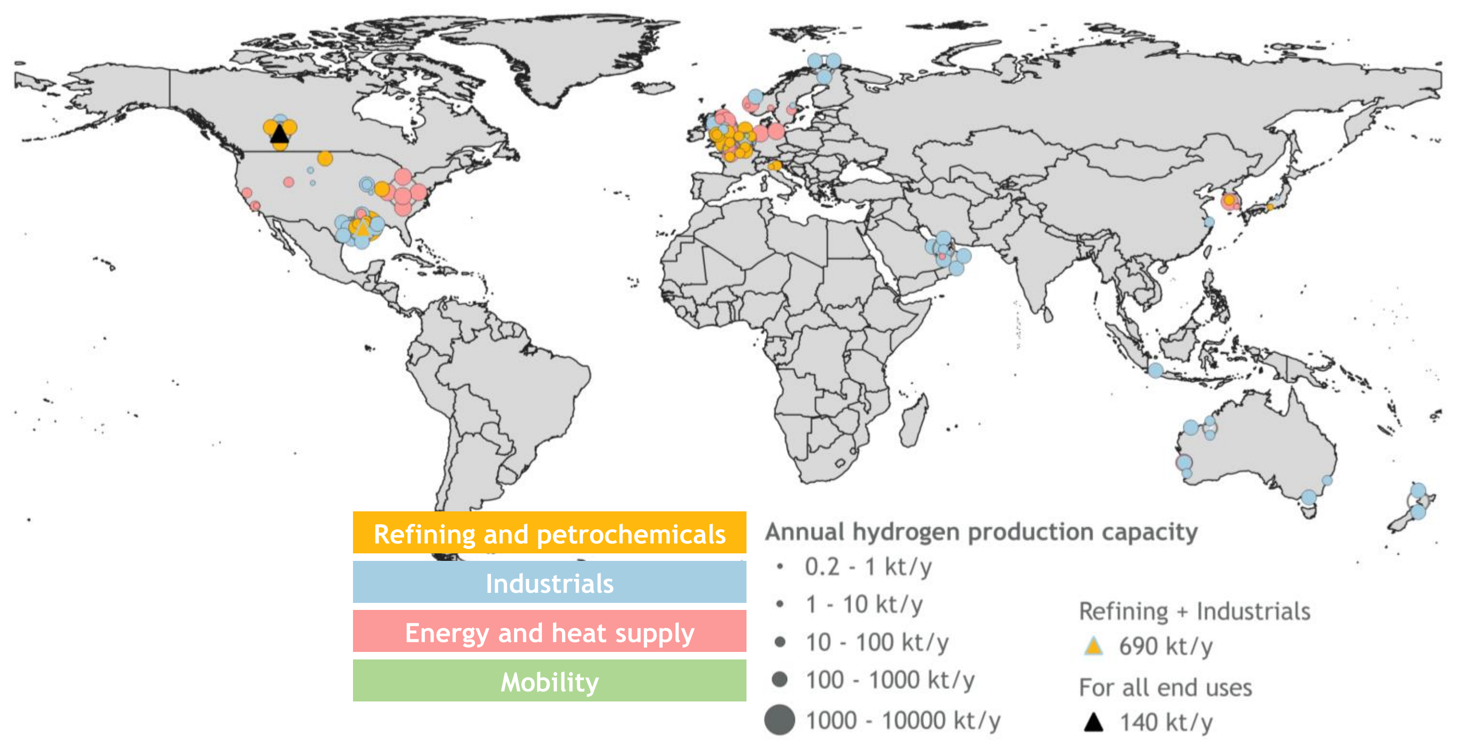
- Fossil-based hydrogen production can only be considered low-carbon in combination with carbon capture and storage.
- In the production of low-carbon hydrogen, steam reforming of natural gas dominates the project landscape for fossil-based hydrogen production.
- In addition to the production of hydrogen from natural gas, there are also projects that produce hydrogen from oil, biomass or on the basis of coal.

1: Own illustration based on IEA (2024) Hydrogen Production and Infrastructure Projects Database

End use: Low-carbon hydrogen production projects

Low-carbon hydrogen is used mostly in the industry sector, refining and petrochemicals

World Map[1]



1: Own illustration based on IEA (2024) Hydrogen Production and Infrastructure Projects Database

Explanation

- The IEA database[1] also contains information on end use, if available. In the following, these are aggregated to refining and petrochemicals, industrials, energy and heat supply and mobility.
- In terms of end use, projects with a predefined end use in the industrial (41 % of total capacity), energy and heat supply (35 %), and refinery and petrochemical sector (20 %) dominate.
- There are also several projects in which energy and heat supply are specified as the intended end use.
- There are only a few projects in which end use is envisaged in the mobility sector, these projects are mostly not equipped with a large production capacity.

Project Spotlight: Wilhelmshaven Energy Hub BlueHyNow

CO_2 transport via pipeline to the Northern sea for offshore storage

Project description

- Wilhelmshaven Energy Hub BlueHyNow[1] is a joint low-carbon hydrogen production project of Wintershall Dea, NOW and Harbour Energy
- **Status:** signed Memorandum of Understanding (August 2022); planned year of operation: 2027
- **CO_2 transport and storage:** transport of captured CO_2 via pipeline to the CO_2 hub “CO2nnectNow” which is also part of Wilhelmshaven Energy Hub
  - The CO_2 hub “CO2nnectNow” enables transportation of CO_2 via rail, ship or local pipeline to CO_2 sinks in the Northern sea
  - The existing natural gas infrastructure is to be converted to transport hydrogen: NWO pipeline network to transport Wintershall Dea's hydrogen to industrial customers
- Current information indicates that the project is delayed. Beginning of operation may be in the 2030s. Challenges in the regulatory framework (e. g. permission of CO_2 export and storage), ramp-up of hydrogen and CO_2 infrastructure and focus on green hydrogen within the incentives on the hydrogen demand side are named as reasons for the delay.

PORT OF WILHELMSHAVEN ENERGY HUB

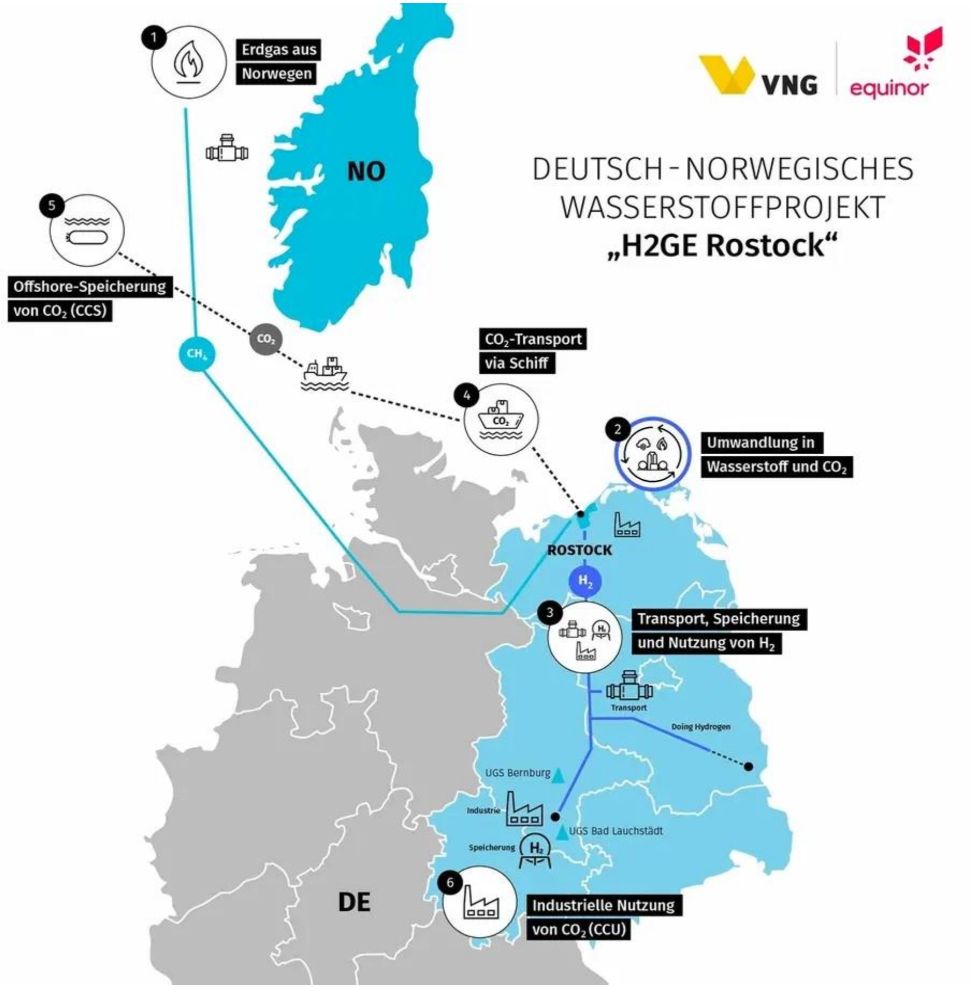
1: Wilhelmshaven Energy Hub (2024)

Project Spotlight: H2GE Rostock

Importing natural gas from Norway to produce low-carbon hydrogen in Germany

Project description

- H2GE Rostock[1] is a joint low-carbon hydrogen production project of VNG and Equinor
- **Status:** Planned (target year of operation: 2030)
- **Technology:** ATR[2] with CCS
- **Production capacity:** the project aims towards a production of up to 210.000 tonnes of low-carbon hydrogen per year (~8-9 TWh → ~10 % of EU low-carbon hydrogen demand in 2030 acc. to TYNDP 2024)
- **CO_2 capture rate:** 95 %, corresponding to around 2 million tonnes of CO_2 per year
- **CO_2 transport and storage:** liquefaction of captured CO_2 and transport via shipping to Offshore CO_2 storage sites
- H2GE is to be connected to the future German hydrogen core network so that the hydrogen produced in Rostock can also be made available to the East German industrial clusters in Brandenburg and Central Germany. This is supposed to strengthen value creation both in Rostock as an industrial location and beyond in the Eastern federal states.



1: HyPower (2024) H2GE Rostock – der Energiehub in Ostdeutschland | 2: Autothermal Reforming, another technology for natural gas reforming

3. Techno-economic analysis

- Scenario definition
- Natural gas supply, steam methane reforming and carbon capturing
- CO_2 transport and storage
- Resulting levelized cost of low-carbon hydrogen
- Technology Readiness Level of CCS processes

Techno-economic analysis of low-carbon hydrogen

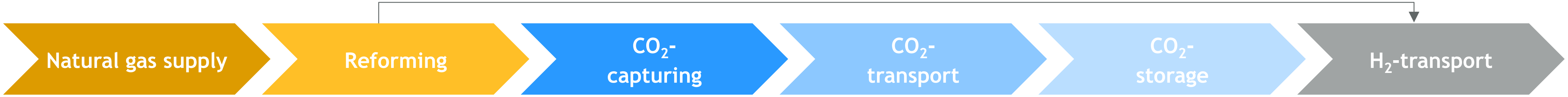
Costs are analyzed based on energy balances and subprocess costs along the value chain

Calculating levelized cost of hydrogen

- The calculation of costs for low-carbon hydrogen must include all steps of the low-carbon hydrogen value chain depicted below.
- The analysis of supply costs is based on the levelized cost of hydrogen (LCOH) approach. Electricity costs, fuel costs, weighted average cost of capital (WACC), specific investment costs, and operation costs are inputs.
- For the production of low-carbon hydrogen, the following process steps are considered:
  - Supply of natural gas from the spot market
  - Steam methane reforming and CO_2 capturing
  - CO_2 transport via pipeline and storage
  - Hydrogen transport

Sensitivities and case studies

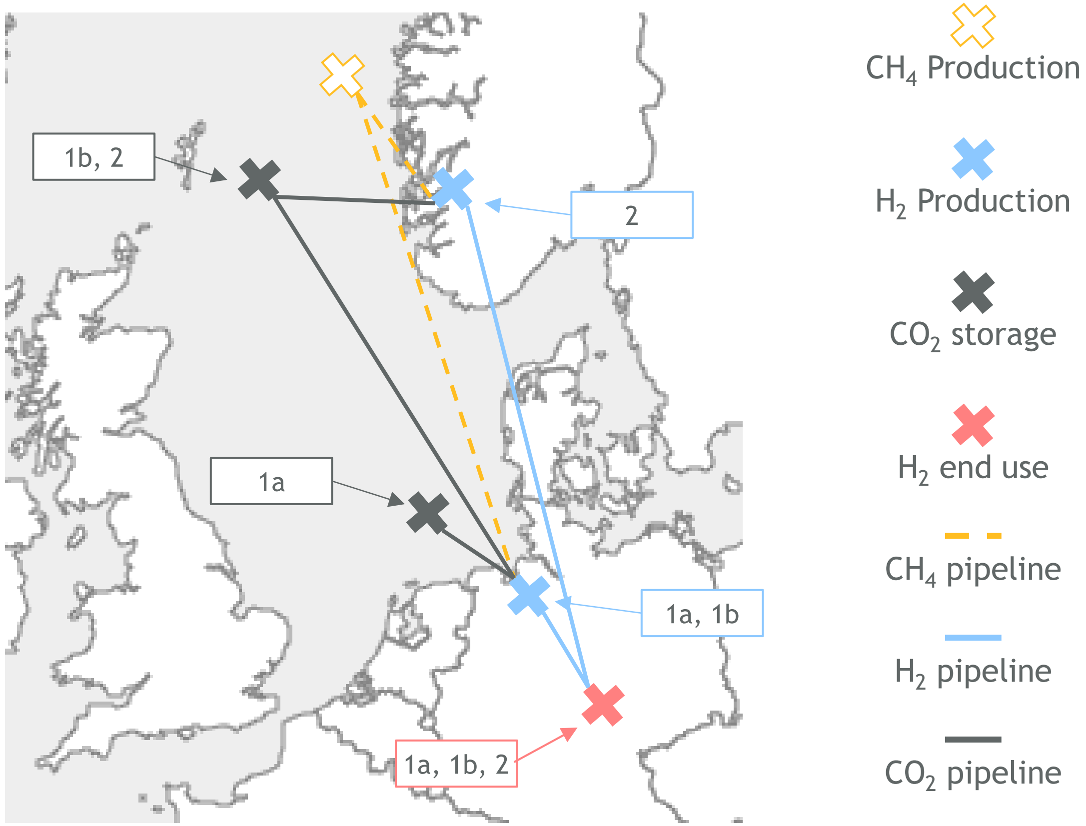
- Major uncertainties of the LCOH are
  - Natural gas, CO_2 and electricity prices
  - Investment conditions, e.g. weighted average cost of capital
  - Scaling effects
  - CO_2 infrastructure costs
- The influence of these parameters is estimated based on sensitivity analyses.
- Additionally, circumstances like the location of hydrogen production and CO_2 storage and resulting transport distances influence low-carbon hydrogen supply costs. These aspects are evaluated within three scenarios.



Techno-economic analysis: Scenario definition

Techno-economic analysis is conducted for three production and transport scenarios

Map of low-carbon hydrogen production scenarios in Europe[1]



Scenario definition

- Three scenarios are defined to represent different case studies. All scenarios assume a uniform natural gas price and the end use of hydrogen in Germany.
- The scenarios differ in transported commodities and storage location.
- Domestic transport is assumed to be 300 km, the transport distance between Germany and Norway is assumed to be 1000 km.

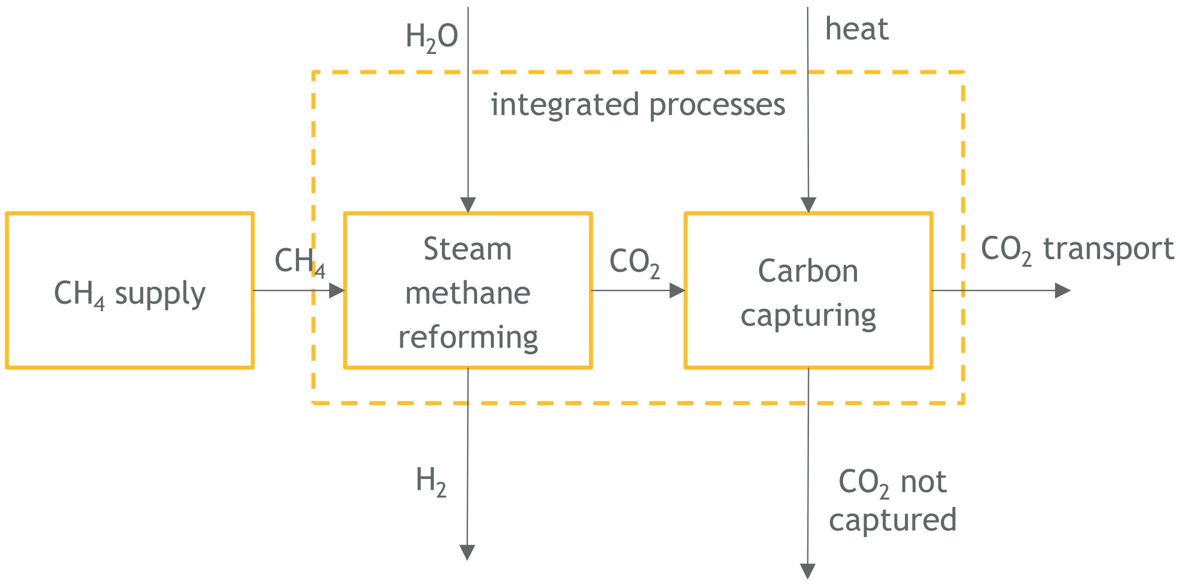
	Scenario 1a	Scenario 1b	Scenario 2
Low-carbon hydrogen production location	Germany	Germany	Norway
CO_2 storage location	Germany (offshore)	Norway (offshore)	Norway (offshore)

1: Locations of CO_2 storages, H_2 production, H_2 end use, and pipelines are exemplary. They are not related to projects.

Natural gas supply, steam methane reforming, and carbon capturing

Steam methane reforming and carbon capturing are often built in an integrated process

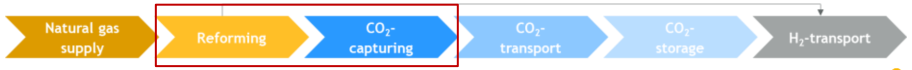
Overview of the steam methane and carbon capturing process



Technoeconomic aspects

- Methane supply
  - Methane is the main input for the production of low-carbon hydrogen, which is why its price drives the production costs.
- Steam methane reforming[1]
  - In the steam methane reforming process methane is reformed to H_2 and CO and later to CO_2 with the water gas shift reaction
  - The overall efficiency defines the required natural gas input
  - CO_2 output is defined by stoichiometry
  - CAPEX and OPEX are considered for the techno-economic analysis
- Carbon capturing
  - In the carbon capture process the bulk of CO_2 emissions are captured, specified by the CO_2 capture rate
  - Steam methane reforming and carbon capturing processes are usually built in one plant to integrate processes

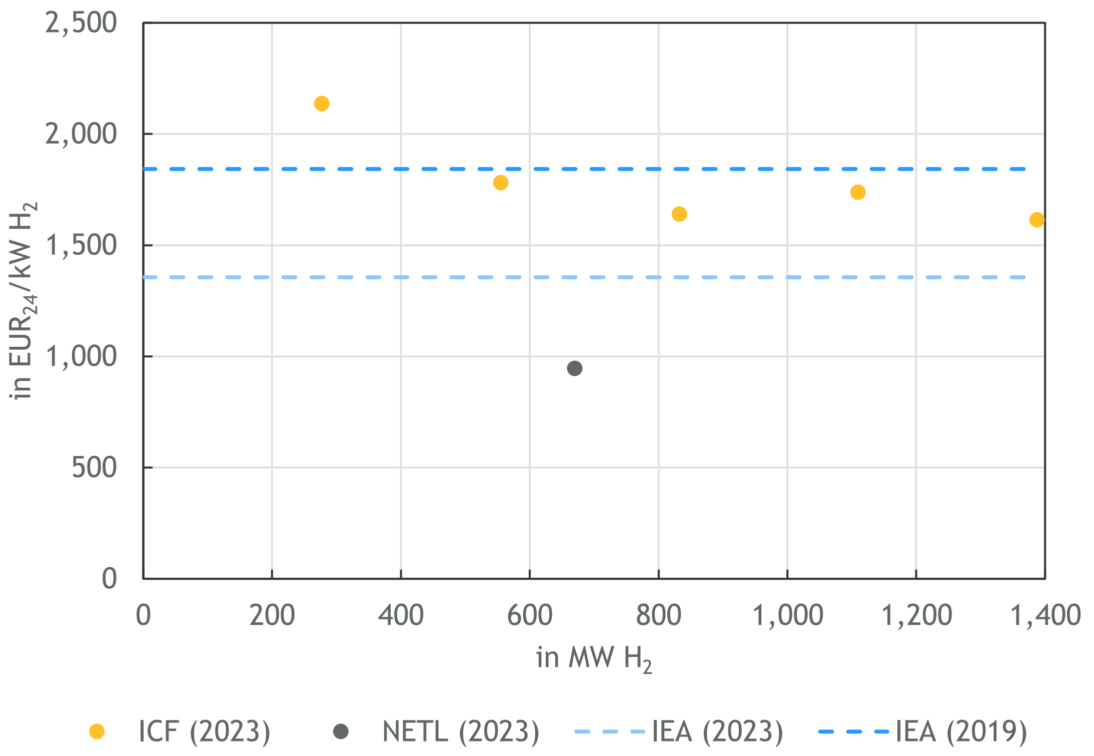
1: This techno-economic analysis focuses on SMR. Autothermal reforming (ATR) combined with CCS is also a promising technology for producing low-carbon hydrogen.



Steam methane reforming and carbon capturing

Specific investment costs of SMR+CC range between 950 and 2,140 EUR/kW H_2

Specific investment costs of steam methane reforming with carbon capturing[1]



Deriving specific investment costs & efficiency for SMR+CC

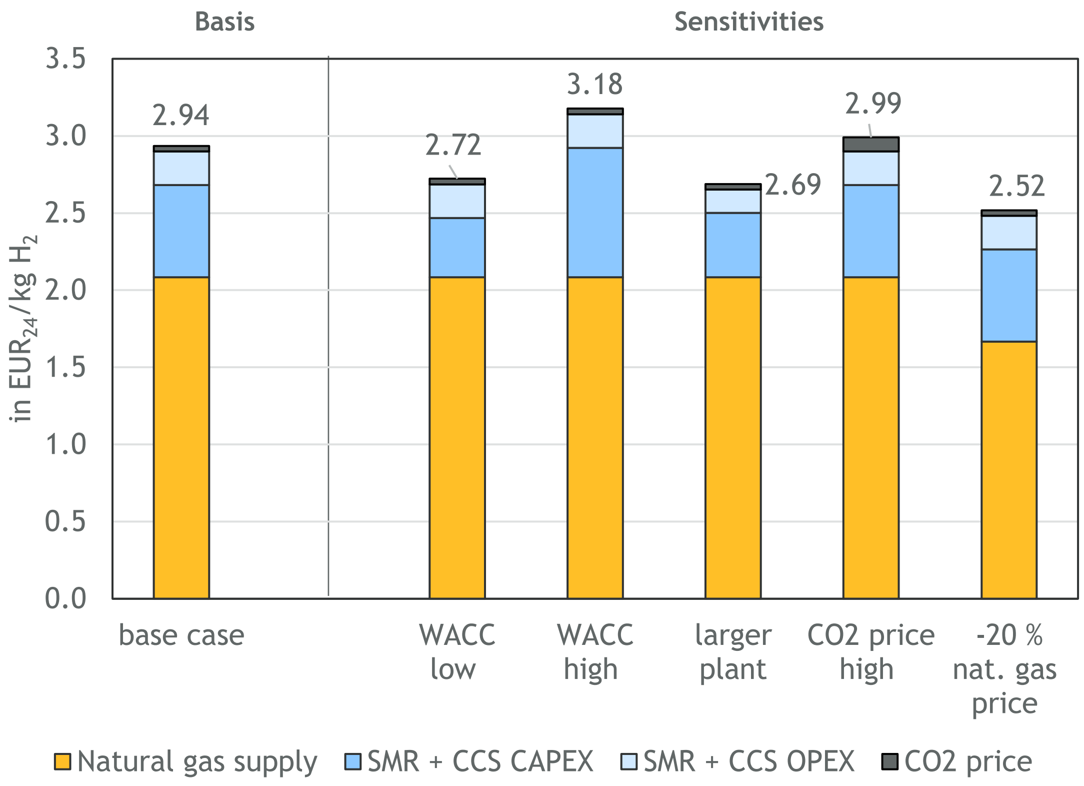
- In current literature, specific investment costs of steam methane reforming and carbon capture range between 950 and 2,140 EUR/kW H_2.
- All plants evaluated here are steam methane reformers with a water gas shift reactor. All these plants use pressure swing adsorption (PSA) for CO_2 capturing and have CO_2 capture rates of around 95 %.
- Larger plants have lower specific investment costs due to economies of scale. Scale effects for chemical plants can be estimated with a 70 % decrease in specific investment costs when doubling the plant size.[2]
- Investment costs for all scenarios are estimated based on IEA (2023) and a sensitivity is calculated based on NETL (2023). Fixed OPEX are assumed to at 4 % of investment costs per year based on IEA (2023).
- The efficiency in MW H_2/MW CH_4 defines the required natural gas input and ranges between 69 % (IEA, 2023) and 72 % (NETL, 2023). The efficiency and the CO_2 capture rate also define CO_2 emissions and CO_2 certification costs.

1: based on ICF (2023), NETL (2023), IEA (2023), and IEA (2019) | 2: Couper et al. (2007)

Hydrogen production costs

Production costs could range between 2.5 and 3.2 EUR/kg (excl. CO_2 transport and storage)

Hydrogen production costs (excl. costs for CO_2 transport and storage)[1]



Comments

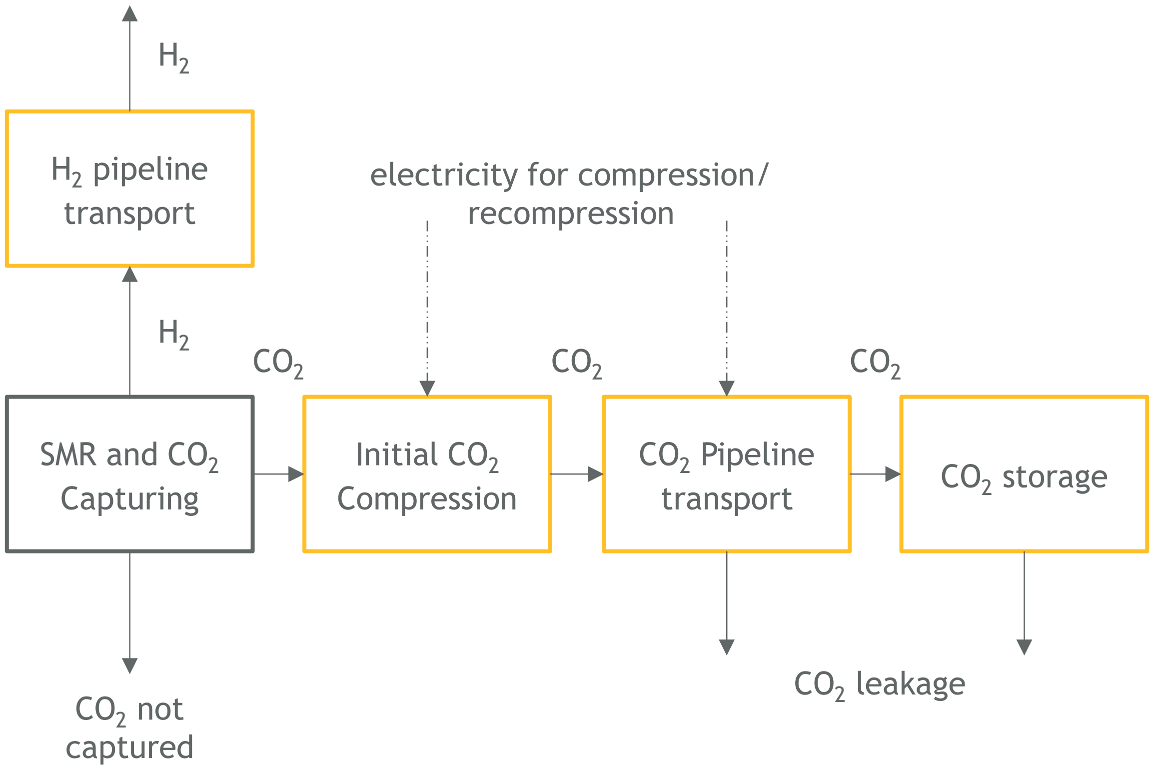
- The diagram shows the production costs of low-carbon hydrogen based on steam reforming and carbon capture with different sensitivities, **without CO_2 follow-up costs.** For calculation of supply costs, the costs for the subsequent transportation and final storage of CO_2 will be added.
- Low-carbon hydrogen production costs range between 2.52 EUR/kg and 3.18 EUR/kg in the exemplary sensitivities.
- A price level of 45 EUR/MWh is assumed for the natural gas supply costs in the base case[2], which is the current TTF natural gas price[3]. The costs for natural gas make up 66 % to 77 % of the total production costs.
- The CAPEX of the steam methane reforming plant with carbon capture account for 16 % to 24 % of the production costs.
- As the natural gas supply is the largest cost component, the natural gas price sensitivity has the largest impact on the production costs. Sensitivities affecting the capital or CO_2 costs have a lower impact on the total production costs.

1: Own calculation based on IEA (2023) Global Hydrogen Review ; Parameters: Weighted Average Cost of Capital (WACC) (low / base / high): 5 % / 10 % / 15 %; CO_2 price (base / high): 80 EUR/t / 200 EUR/t; Natural gas price (base / low): 45 EUR/MWh / 36 EUR/MWh | 2: In Norway, 45 EUR/MWh would reflect opportunity costs from not selling natural gas to the TTF market. | 3: EEX databasis | Costs in EUR 2024

CO_2 transport and storage and H_2 transport

Several subprocesses must be considered for the CO_2 transport and storage analysis

Overview of CO_2 transport and storage processes



Techno-economic aspects

- After CO_2 capturing, the CO_2 is compressed to around 135 bar for pipeline transport, which leads to initial compression costs. During transport, recompression takes place.[1]
- For the cost calculation of CO_2 transport and storage, CAPEX, OPEX, and energy demands of all processes must be considered.
- Moreover, CO_2 leakage and the CO_2 intensity of the energy required for CO_2 transportation (e.g. electricity for compression or fuel for shipping) have to be considered to calculate CO_2 emissions compliant with the EU Commission Methodology to determine the greenhouse gas (GHG) emission savings of low-carbon fuels[2].
- Calculating costs and emissions for CO_2 transport and storage is associated with uncertainty as CO_2 infrastructure currently does not exist as it is required for large-scale production of low-carbon hydrogen.
- Shipping may offer an alternative for CO_2 transport of small quantities, with lower initial investment and construction requirements. However, this analysis focuses on large-scale transport via pipelines.

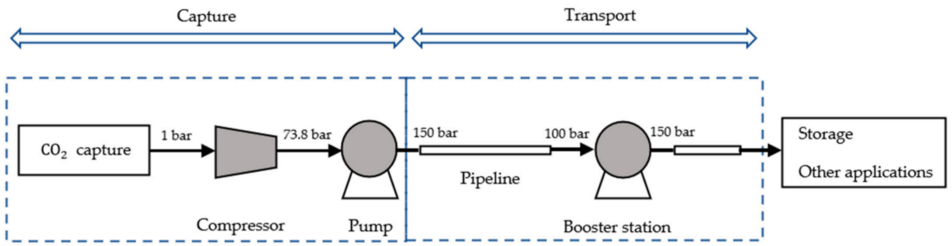
1: Solomon et al. (2024) | 2: EC (2024a) Directive (EU) 2024/1788, see also Chapter 4

CO_2 pipeline transport (1/4): Initial compression

Initial compression costs are around 17 EUR/ t CO_2 for an electricity price of 100 EUR/MWh

Calculating electricity demand for CO_2 compression[1]

From gaseous to dense state in two stages via compressor and pump:



Electricity demand for compressor:

$$w_{comp} = \frac{Z_S \cdot R \cdot T_{in,comp}}{\eta_{is,comp}} \cdot \frac{k_S}{k_S - 1} \cdot \left(\frac{p_{cut-off}}{p_{initial}}^{\frac{k_S - 1}{k_S}} - 1 \right) \quad (1)$$

with: $$k_S = \frac{c_p}{c_v} \quad (2)$$

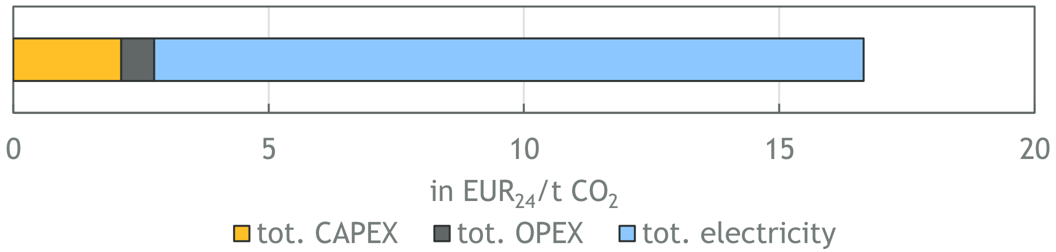
Electricity demand for pump:

$$w_{pump} = \frac{p_{final} - p_{cut-off}}{\rho \cdot \eta_p} \quad (3)$$

Deriving initial compression costs[2]

- Electricity demand for compression and pumping is a decisive cost component and relevant to the total emission calculation.
- Compressor: 0,48 MJ/kg CO_2 electricity is required with an isentropic compression efficiency of 75 %.
- Pump: 0.02 MJ/kg CO_2 electricity is required with an efficiency of 75 %.
- Considering compressor and pump CAPEX and OPEX and an electricity price of 100 EUR/MWh results in total compression costs of 16.65 EUR/t CO_2 equivalent to 4.53 EUR/MWh H_2 for a CO_2 capture rate of 95 %.

Total compression and pumping costs:

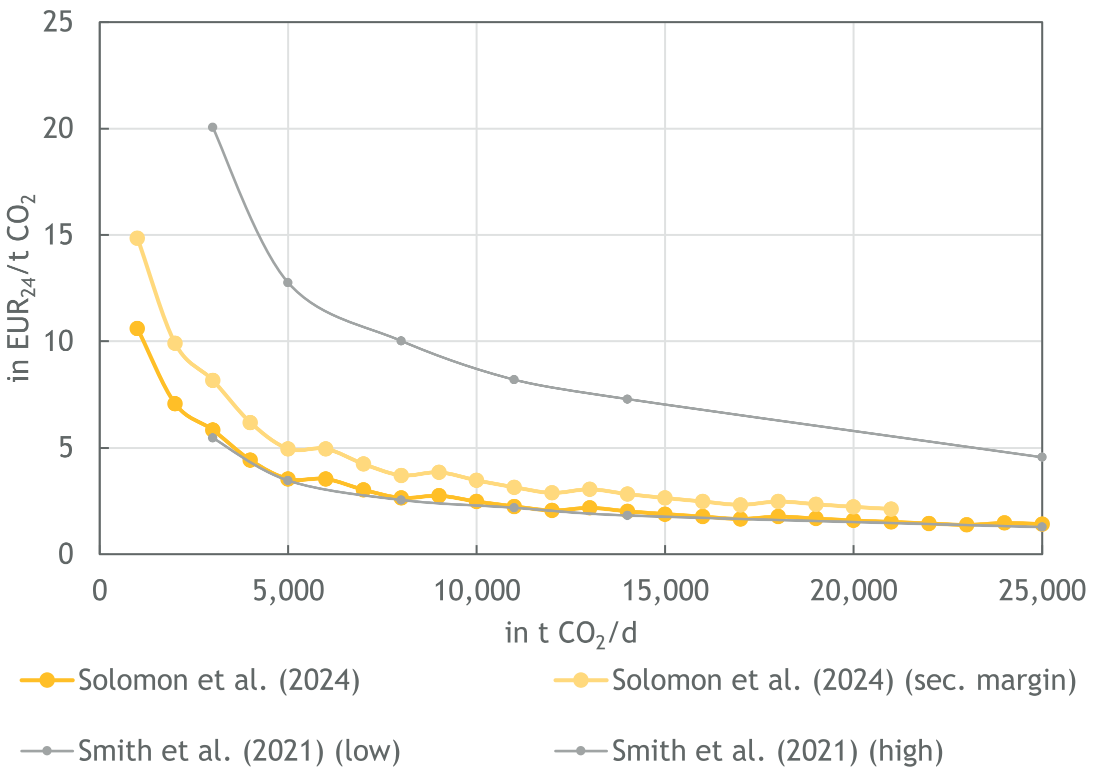


1: based on Solomon et al. (2024) | 2: Own calculation: k_s = 1,33, Zs = 0.9, $p_{cut-off}$ = 73.8 bar, $p_{initial}$ = 1 bar : p_{final} = 150 bar, ρ_{CO2} = 650 kg/m_2 (for 35°C and 100 bar), I_{comp} = 854 EUR/kW, I_{pump} = 51 EUR/kW, Oversizing = 1/1.1, utilization = 90 %, OPEX = 4 % of CAPEX/a, WACC = 10 %, lifetime = 15 years

CO_2 transport costs (2/4): Pipeline

CO_2 transport costs via pipeline decline with higher mass flow

CO_2 transport costs for 100 km pipeline (without init. compression)[1]



Interpretation

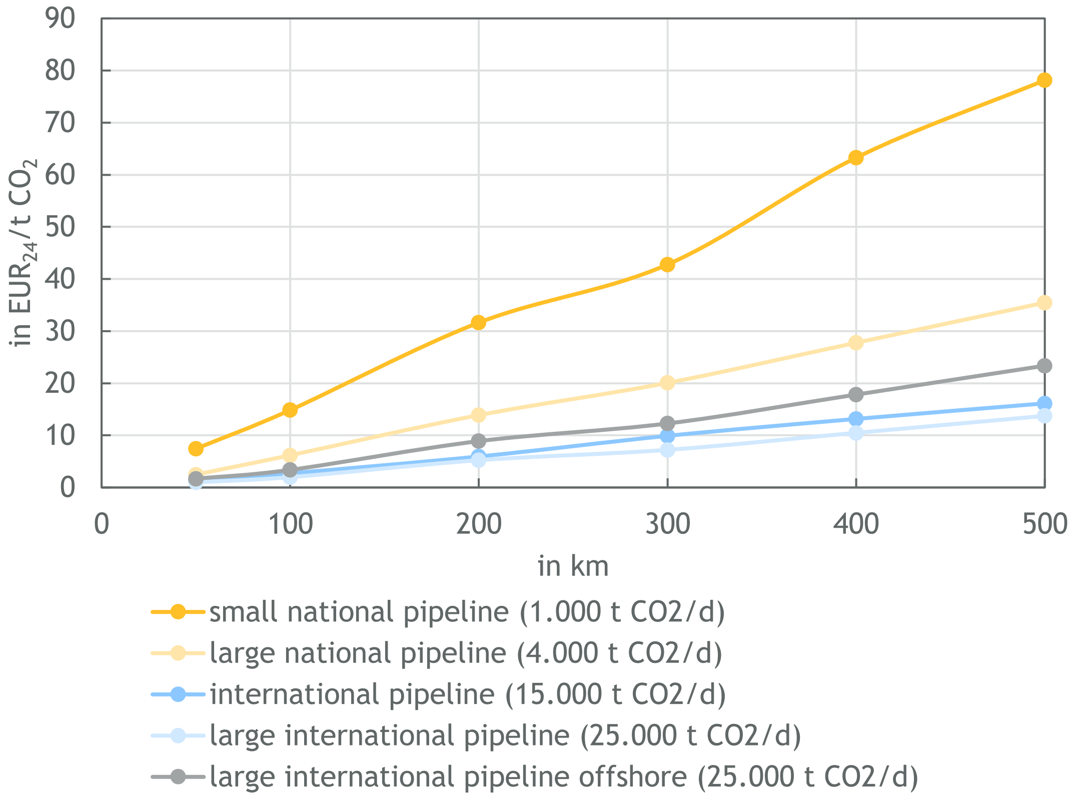
- The diagram shows specific CO_2 transport costs for different mass flows based on Solomon et al. (2024) and Smith et al. (2021).
- The relation between specific transport costs and mass flows is roughly anti-proportional when only considering the pipeline construction costs.
- Recompression occurs when the initial pressure of 130 bar drops by 50-70 bar, and the CO_2 is no longer in a supercritical state. The pressure loss per section is linearly anti-proportional to the diameter and quadratic to the velocity, which is increased by the preceding pressure loss.
- Solomon et al. (2024) calculate the optimal pipeline diameter for each mass flow and transport length combination, which also depends on the pressure loss and thus the recompression requirement. The optimal solution is therefore always found, which is why the result might be close to the lower cost estimate of Smith et al. (2021).
- For the techno-economic analysis, the costs of Solomon et al. (2024) are considered with a safety margin of 40 % to account for uncertainties regarding capacity utilization and dimensioning.

1: based on Solomon et al. (2024) and Smith et al. (2021)

CO_2 transport costs (3/4): Pipeline

CO_2 transport costs via pipeline decline with higher mass flow

CO_2 transport costs of different pipelines (without init. compression)[1]



Interpretation

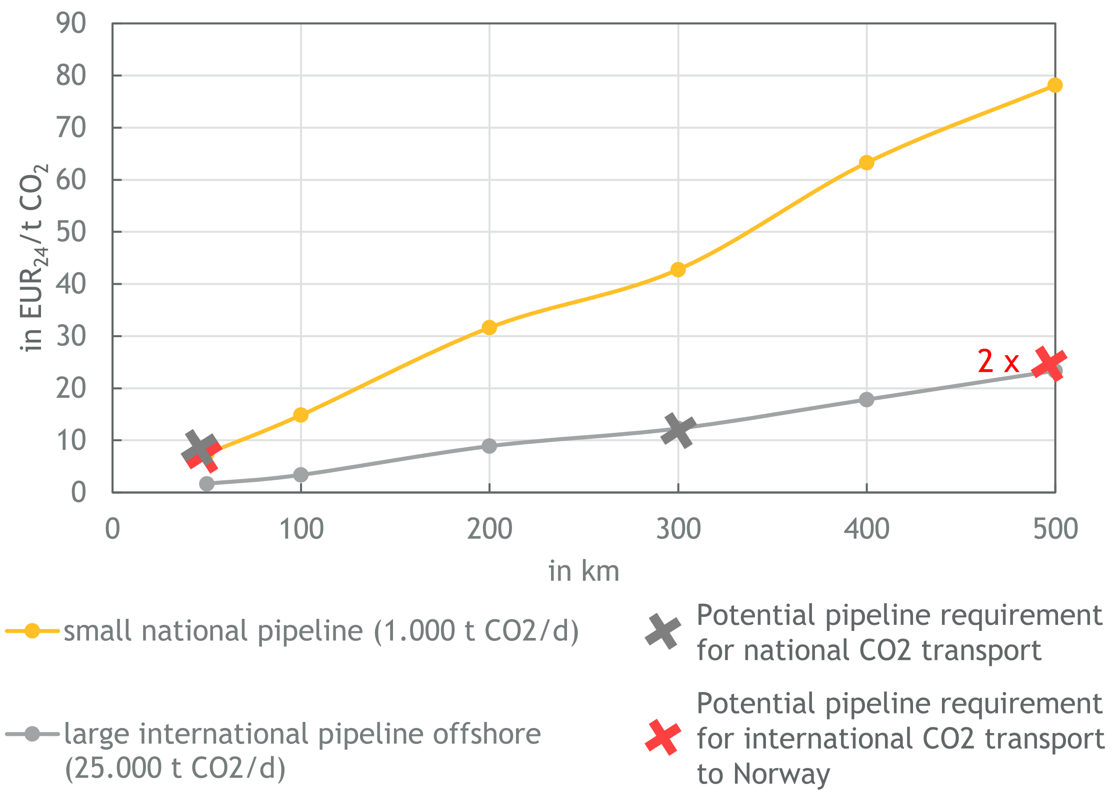
- The diagram shows the transport costs of CO_2 for different pipeline sizes based on Solomon et al. (2024).
- A pipeline with a capacity of 1,000 t CO_2/d can transport the CO_2 from a plant producing approx. 100 t low-carbon hydrogen per day (approx. 30,000 t H_2/a or 1 TWh H_2/a) at a CO_2 capture rate of 95 %.
- A pipeline with a capacity of 25,000 t CO2/d can transport 7.5 million t CO_2 per year at high utilization. The CO_2 from the production of up to 1 million tons of low-carbon hydrogen (around 33.3 TWh/a) can be transported at a CO_2 capture rate of 95 %. Large pipelines could also combine CO_2 flows from different CO_2 sources bringing them to one sink.
- Costs of Offshore pipelines are assumed to be 70 % higher based on the European Hydrogen backbone (2023).
- The pipeline capacity requirements depend on the transport scenario and are driven by the location of the production site, the location of the CO_2 storage, and the amount of CO_2 transport.

1: based on Solomon et al. (2024) and a safety margin of 40 % regarding utilization and dimensioning, for the Offshore pipeline 70 % of Onshore transport costs are added based on European Hydrogen Backbone (2023)

CO_2 transport costs (4/4): Pipeline scenario

CO_2 transport demands depend on the transport scenario

CO_2 transport costs of different pipelines (without init. compression)[1]



Calculation of total CO_2 transport costs including compression

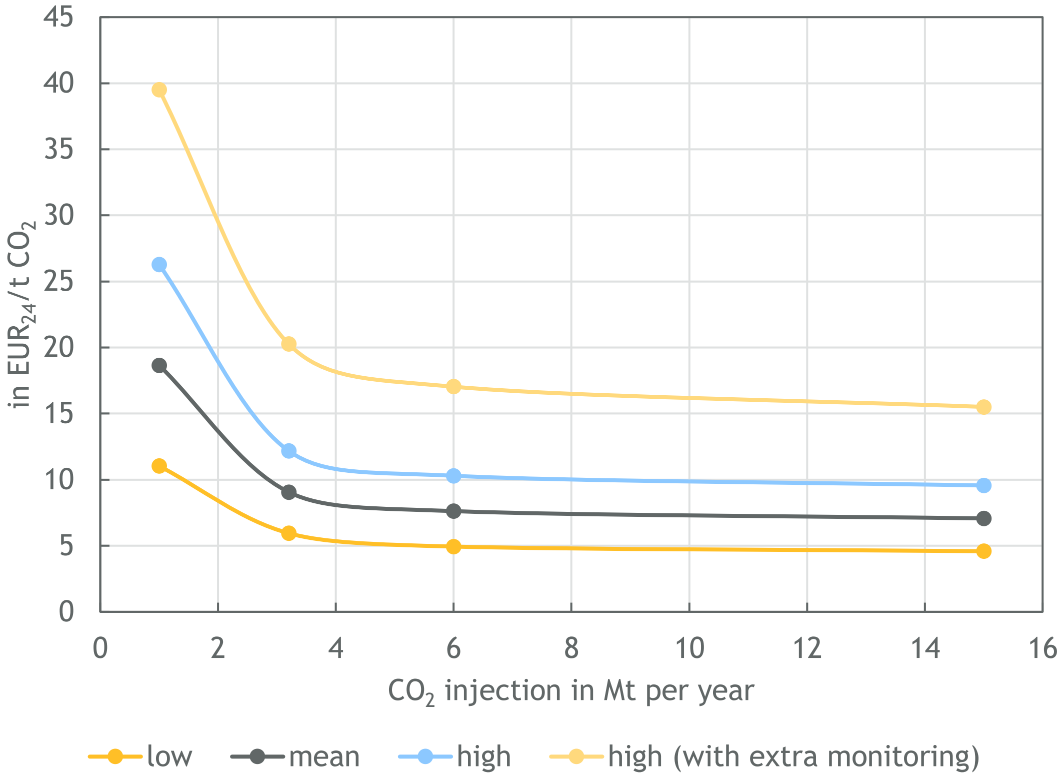
- CO_2 Pipeline transport demands and therefore CO_2 Pipeline transport costs depend on the transport scenario.
- In all scenarios, 50 km onshore transport in a small national pipeline is assumed.
- In scenarios where CO_2 storage is located in Germany, same as the hydrogen production site (scenario 1a and scenario 2), 300 km transport in a large offshore pipeline is assumed.
- In the scenario where CO_2 storage is located in Norway and the H_2 production in Germany (scenario 1b), 1,000 km transport in a large offshore pipeline is assumed.
- In a sensitivity, no CO_2 transport in a small national pipeline is required.

1: based on Solomon et al. (2024) and a safety margin of 40 % regarding utilization and dimensioning | 2: Own calculation based on Solomon et al. (2024), a CO_2 capture rate of 95 % and an electricity price of 100 EUR/MWh

CO_2 storage costs

Geologic characteristics, scale and monitoring requirements drive CO_2 storage costs

CO_2 storage costs depending on injection per year for different scenarios[1]



1: based on Smith et al. (2021)

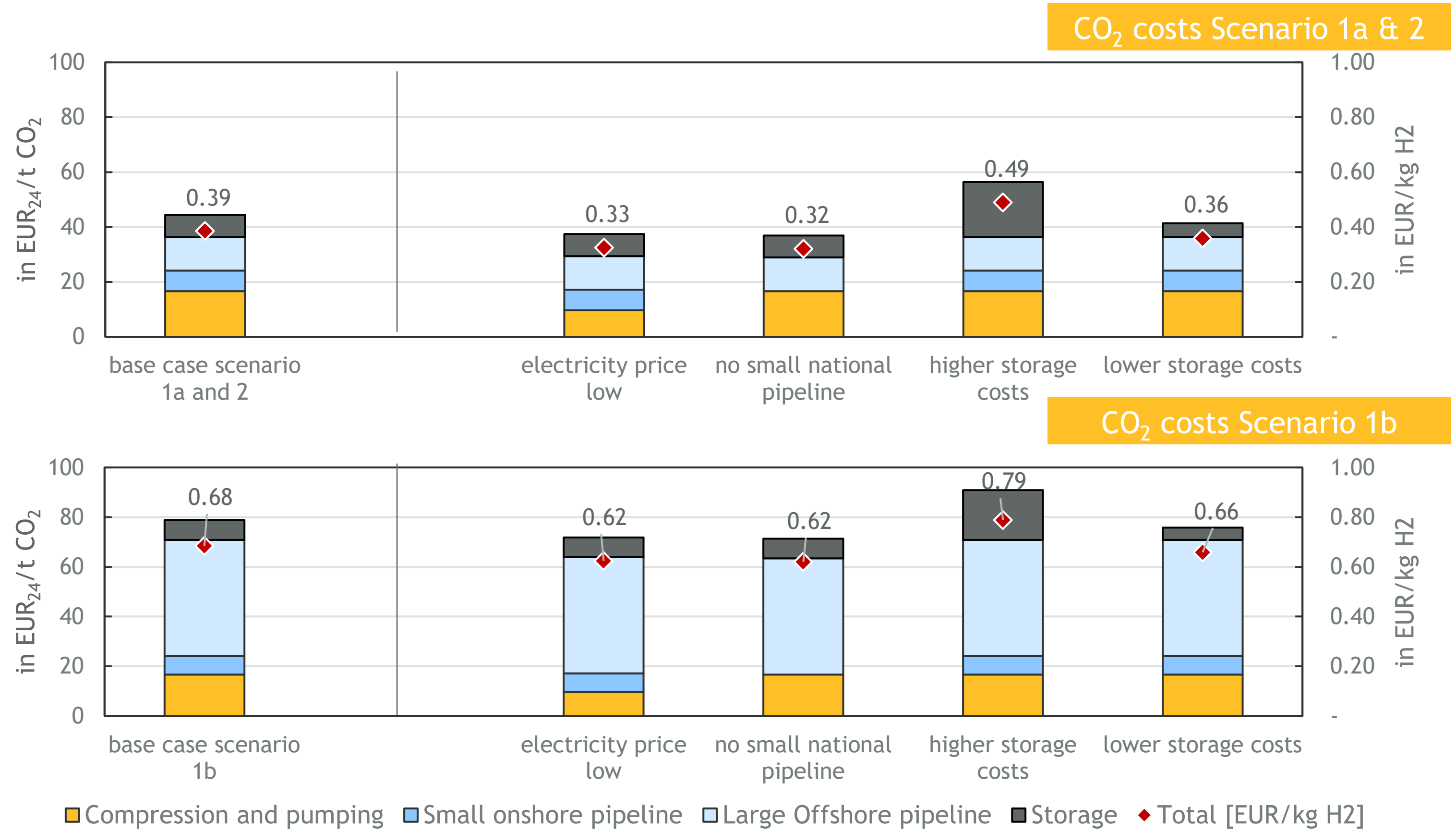
Deriving CO_2 storage costs

- Three sources of variability in CO_2 storage costs:
  - Geologic characteristics
  - Scale (sensitivity)
  - Financing/ Monitoring requirements.
- These parameters determine the total CO_2 volume that can be injected into a reservoir and the maximum rate of CO_2 injection per injection well, which determines the number of injection wells required.
- For all scenarios, CO_2 storage costs for the mean scenario and a CO_2 injection of 6 Mt per year are considered (8 EUR/t CO_2).
- A sensitivity analysis with low CO_2 storage costs (low-cost scenario and injection of 15 Mt per year, 5 EUR/t CO_2) is conducted.
- A sensitivity analysis with high CO_2 storage costs (high-cost scenario with extra monitoring and injection of 3.2 Mt per year, 20 EUR/t CO_2) is conducted.

CO_2 transport and storage costs: Results

Costs can be around two times higher for longer distance international CO_2 transport

CO_2 transport and storage costs[1]



1: CO_2 capture rate: 95 %

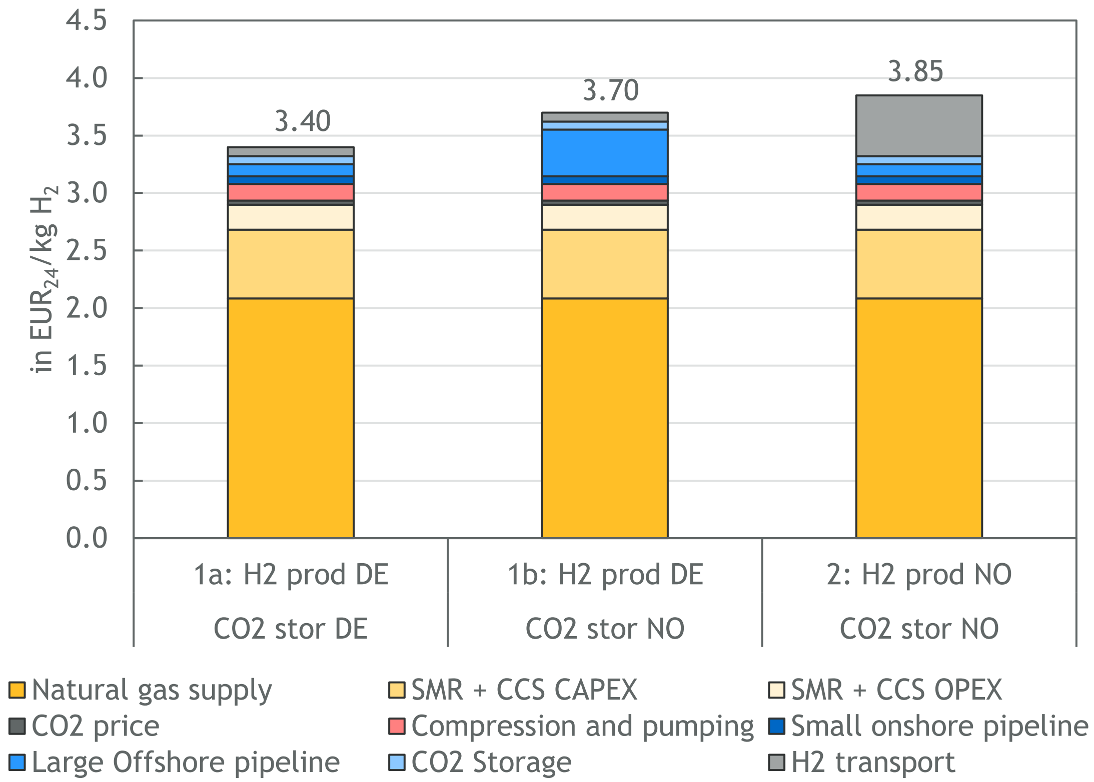
Interpretation

- The diagram shows the CO_2 transport and storage costs for the scenarios of domestic storage (Scenarios 1a & 2) and the scenario with storage in a different country with a longer offshore transport distance (Scenario 1b) with different sensitivities.
- In the domestic CO_2 storage scenarios, the total costs for CO_2 transport and storage range from 0.32 EUR/kg H_2 to 0.49 EUR/kg H_2. Compression and pumping accounts for 26 % to 45 % of the CO_2 costs. Storage costs can have a share of up to 35 %.
- In the scenario with transport from Germany to Norway, the total costs for CO_2 transport and storage range from 0.62 EUR/kg H_2 to 0.79 EUR/kg H_2. The offshore pipeline accounts for up to 65 % of total transport and storage costs.

Techno-economic analysis: Total results

Low-carbon hydrogen production in Germany might lead to lower supply costs to Germany than production in Norway

Supply costs of low-carbon hydrogen for end use in Germany



Interpretation

- The diagram shows an estimate of supply costs for low-carbon hydrogen for Germany in three scenarios. In scenario 1a, hydrogen is produced and CO_2 is stored in Germany. In scenario 1b, hydrogen is produced in Germany and CO_2 is stored in Norway. In scenario 2, hydrogen is produced and CO_2 is stored in Norway.
- Under the given assumptions, the total supply costs are between 3.40 EUR/kg H_2 and 3.85 EUR/kg H_2. For all scenarios, the natural gas supply is the largest cost component. A sensitivity of the natural gas price showed that a natural gas price decrease from 45 EUR/MWh to 36 EUR/MWh (-20 %) reduces production costs by 0.42 EUR/kg H_2.
- CO_2 and H_2 transport and CO_2 storage costs add between 0.56 and 0.91 EUR/kg H_2 in this analysis. The sensitivity analysis suggests that electricity prices for CO_2 compression, direct CO_2 pipeline access and scale of CO_2 storages can noticeably influence these cost components.
- CO_2 transport costs might be lower than hydrogen transport costs, resulting in lower supply costs when hydrogen transport is minimized.

1: EWI analysis | 2: Assumptions: natural gas price: 45 EUR/MWh, other cost assumptions in chapter before and based on EWI (2024) Global PtX Cost Tool | transport distances: scenario 1a: H_2: 300 km onshore, CO_2: 300 km offshore; scenario 1b: H_2: 300 km onshore, CO_2: 1000 km offshore; H_2: 1000 km offshore and 300 km onshore, CO_2: 300 km offshore

Technology Readiness Level of carbon capture and storage

Most subprocesses are already classified as commercial in a relevant environment

Technology Readiness Level (TRL) of carbon capture and storage processes[1]

Process step	Subprocess/ technology	TRL
Carbon capture process	Carbon capture after SMR	9
	Carbon capture at high capture rates after SMR	6
CO_2 transport	Pipeline	10
	Shipping	7
CO_2 storage	Advanced monitoring technologies	8
	CO_2-enhanced oil recovery	11
	Depleted oil and gas reservoir	8
	Saline formation	9

Comments

- The process of steam methane reforming (SMR) of natural gas has been commercially operational at large scale for many years to produce grey hydrogen. Most of the CCS subprocesses already show a TRL for a commercial operation in a relevant environment (TRL ≥ 9). Lower TRL might result in higher investment risks as well as scaling challenges.
- For the carbon capture process after SMR, different technologies are available. Carbon capture technologies in the context of SMR can be physical adsorption technologies like pressure swing adsorption (PSA) or chemical adsorption/ absorption technologies based on methyl diethanolamine or other materials. Higher capture rates can be achieved for autothermal reforming (ATR), but the TRL is significantly lower and a higher natural gas feed-in is required for ATR.[2]
- CO_2 pipeline transport has a high TRL of 10, however, a public CO_2 network are not in place yet in the EU. The TRL of CO_2 shipping is significantly lower with 7 (pre-commercial demonstration). The TRL of CO_2 storage varies with the geologic formation. CO_2-enhanced oil recovery and saline formation have a TRL of 9 or higher.

1: based on IEA (2024) ETP Clean Energy Technology Guide | TRL: 6 (full prototype at scale), 7 (pre-commercial demonstration), 8 (first of a kind commercial), 9 (commercial operation in relevant environment), 10 (integration needed at scale), 11 (proof of stability reached) | 2: Riemer & Duscha (2022)

4. Regulatory framework

- Regulatory framework at the EU level
  - Delegated Act on low-carbon fuels
  - EU Taxonomy
  - CO_2 Infrastructure
  - Hydrogen demand
  - Hydrogen funding programs
- Regulatory framework at national level in Germany
  - National Hydrogen strategy
  - Import strategy for hydrogen and derivatives
  - Carbon Management strategy
  - Carbon Dioxide Storage Act
  - Hydrogen demand
- Outlook

Overview of regulatory milestones in the EU and Germany

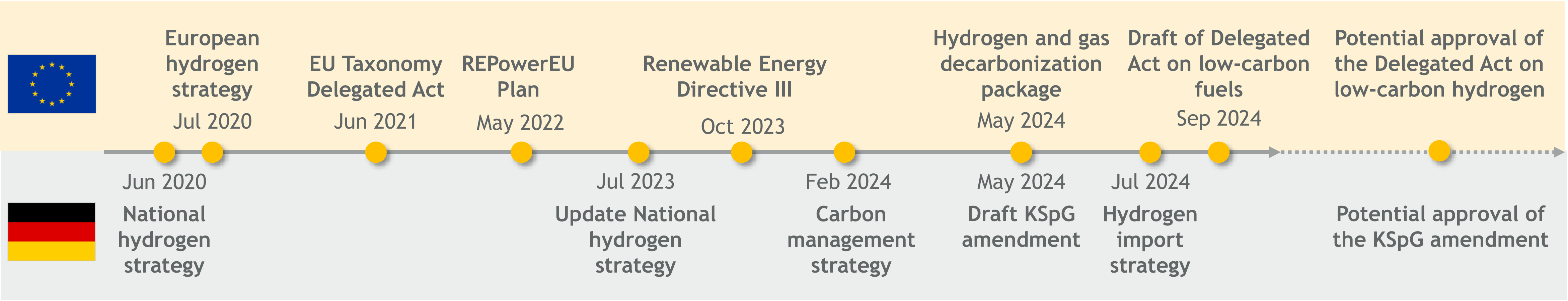
The regulatory landscape for low-carbon hydrogen is still being developed

Background

- The regulatory framework is an important component in the hydrogen market ramp-up. The EU level framework may give the definition of low-carbon hydrogen and how it may be promoted and utilized.
- Currently, the framework is still being developed regarding various aspects. This chapter will provide an overview of the already approved and planned framework and highlight possible implications.

Status Quo

- In general, regulation at European and federal level complement each other. The following chapter therefore takes a closer look at the EU's and German regulation on low-carbon hydrogen.
- Strategy documents, legal definitions of low-carbon hydrogen and the laws governing the production of hydrogen from natural gas combined with the capture and storage of hydrogen will be examined.



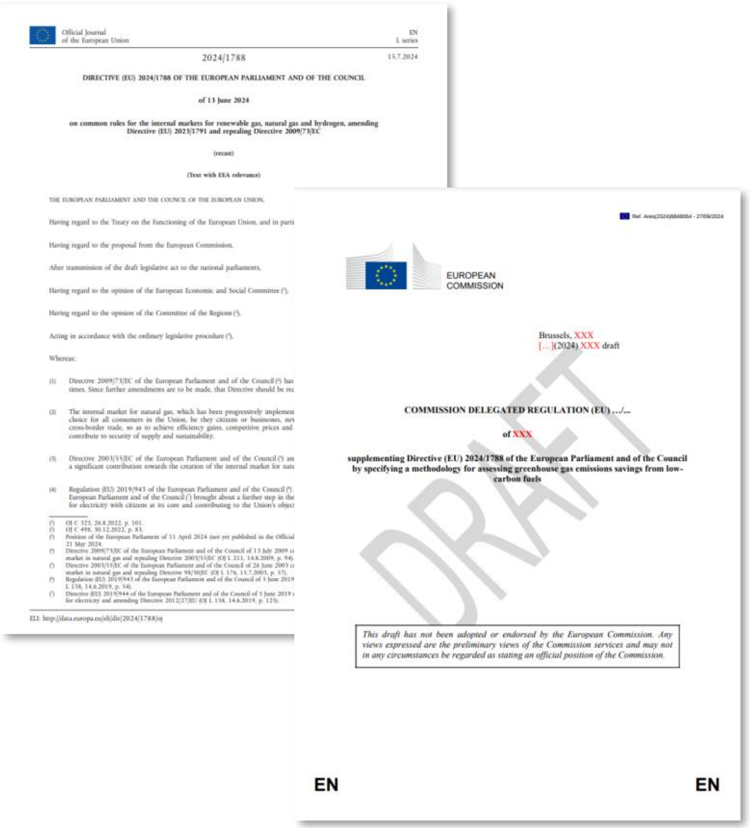
Regulatory framework on EU level: Hydrogen production

Low-carbon hydrogen is defined in the Delegated Act on low-carbon fuels

EU Directive 2024/1788 and the associated Delegated act

- The EU package for hydrogen and gas decarbonization was adopted in May 2024. The package consists of two directives, Directive (EU) 2024/1788 & 1789[1]. The first directive regulates, among other things, the certification of low-carbon fuels. Specifically, Article 9 obliges the EU Commission to introduce a delegated act by August 2025 in which the methodology for calculating emission savings from low-emission fuels is defined.
- A delegated act is a non-legislative act adopted by the European Commission that serves to amend or supplement the non-essential elements of the legislation[2]. In the context of low-carbon hydrogen, the relevant delegated act supplements the Directive (EU) 2024/1788 by specifying the central definition of low-carbon hydrogen[3]. It provides the methodology for calculating greenhouse gas emissions and emission savings from low-carbon fuels.
- In September 2024, the EU Commission launched the consultation on the draft for the Delegated act on low-carbon hydrogen and gathered comments from stakeholders. The final Delegated act is planned to be adopted and published by Q1 2025. The member states would then have to translate the EU directive into national law until mid-2026.

Documents[1,3]


Official Journal of the European Union

2024/1788

DIRECTIVE (EU) 2024/1788 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 13 June 2024

on common rules for the internal markets for renewable gas, natural gas and hydrogen, amending Directive (EU) 2023/1791 and repealing Directive 2009/73/EC

(recast)

(Text with EEA relevance)

EUROPEAN COMMISSION

Brussels, XXX
[…](2024) XXX draft

COMMISSION DELEGATED REGULATION (EU) …/…

of XXX

supplementing Directive (EU) 2024/1788 of the European Parliament and of the Council by specifying a methodology for assessing greenhouse gas emissions savings from low-carbon fuels

DRAFT

EN EN

1: EC (2024a) Directive (EU) 2024/1788 | 2: EC (2024b) Delegated acts | 3: EC (2024c) Commission Delegated Regulation (EU) …/… supplementing Directive (EU) 20241788

Regulatory framework on EU level: Hydrogen production

What qualifies as low-carbon hydrogen in the Delegated Act on low-carbon fuels?

Emissions are computed along the value chain and compared to its fossil comparator

- According to the draft of the delegated act, all emissions along the value chain must be considered. These include the (upstream) emissions from the raw material, e.g. natural gas, the emissions from processing, distribution and transportation as well as the end use. These emissions are compared to the captured and stored/used emissions defined by Regulation (EU) 2018/2066. Emissions resulting from storage through compression, liquefaction, transportation and injection must also be considered. In contrast to upstream emissions, these emissions are not standardized but computed for each case individually. In formula this reads as follows[1]:

$$E = e_i + e_p + e_{td} + e_u - e_{CCS} - e_{CCU}$$

- According to the draft[1], for a fuel to be considered as low-carbon, at least 70 % of the emissions must be saved compared to a fossil comparator defined by the Delegated Regulation (EU) 2023/1185.

$$Savings = \frac{E_F - E}{E_F}$$

- The focus of this research report is hydrogen production from natural gas combined with the capturing of emissions. In this case, natural gas is the fossil comparator. It is assumed to have emissions of 94 g CO_2 eq./MJ (Delegated Regulation (EU) 2023/1185). Compared to this value, a **70 % reduction** in emissions must be realized to be considered low-carbon. In terms of residual emissions this implies that low-carbon hydrogen must meet a threshold of 3.38 kg CO_2/kg H_2.

1: EC (2024) Annex on Directive (EU) 2024/1788

Nomenclature[1]

- E = *total emissions from the production and the use of the fuel*
- E_F = *total emission from fossil comparator*
- e_i = *emissions from supply of inputs*
- e_p = *emissions from processing*
- e_{td} = *emissions from transport and distribution*
- e_u = *emissions from combusting the fuel in its end use*
- $e_{CCU/S}$ = *net emission savings from capturing*

Regulatory framework on EU level: Hydrogen production

A simplified approach to estimating the emissions from low-carbon hydrogen

Emissions are computed along the value chain and compared to its fossil comparator

- This analysis does not claim to provide a perfectly regulation-compliant calculation of emissions for all variants of use cases. Instead, an exemplary and simplified calculation for the production of low-carbon hydrogen from natural gas with CCU/S is performed as follows.

Natural gas supply	Reforming	CO_2-capturing	CO_2-transport	CO_2-storage
Upstream emissions, incl. leakage(s) Referred to as $e_{i_{NG}}$	Combustion and process emissions Referred to as $e_{p_{NG}}$	Captured CO_2 emissions Referred to as $e_{cap_{CO_2}}$	Emissions from compression for CO_2 transport and storage as well as leakages Referred to as $e_{t_{CO_2}} + e_{s_{CO_2}}$	

- In a simplified approach, the emissions and net savings along the value chain are calculated as follows:

$$E = e_{i_{NG}} + e_{p_{NG}} - e_{cap_{CO_2}} + e_{t_{CO_2}} + e_{s_{CO_2}}, \text{ where } e_{CCU/S} = e_{cap_{CO_2}} - \left(e_{t_{CO_2}} + e_{s_{CO_2}}\right)$$

- While up- and midstream emissions related to natural gas ($e_{i_{NG}} + e_{p_{NG}}$) to be assumed are specified by the Delegated Act, emissions from transport and storage must be calculated individually for each use case. In the following calculations, the subsequent emissions represent an example case.

Nomenclature

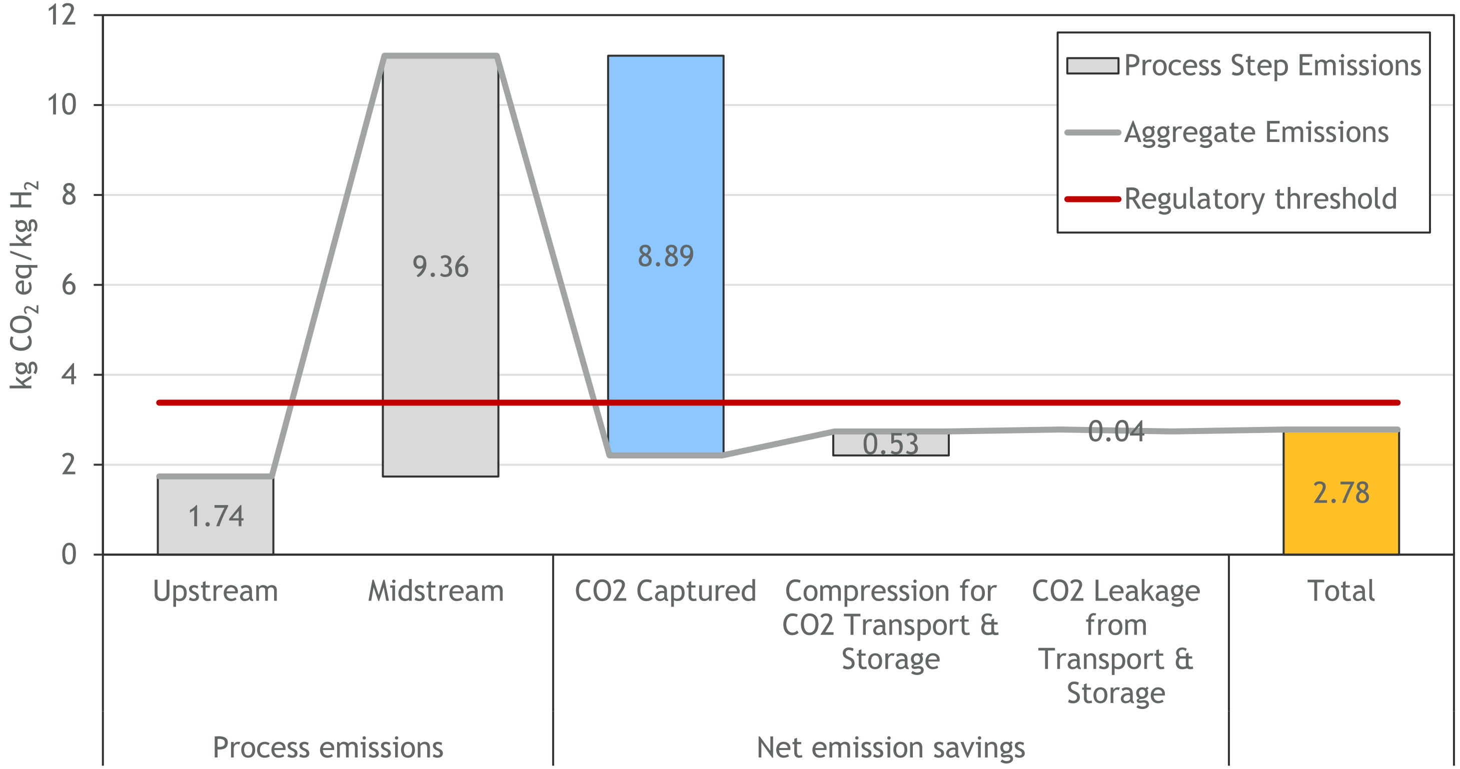
- $E = total\ emissions\ from\ the\ use\ of\ the\ fuel$
- $e_{i_{NG}} = emissions\ from\ supply\ of\ inputs, i.e.\ natural\ gas (10.45\ g\ CO_2\ eq./MJ^1)$
- $e_{p_{NG}} = emissions\ from\ processing\ of\ natural\ gas\ (56.2\ gCO_2\ eq./MJ\ ^1)$
- $e_{cap_{CO_2}} = captured\ emission\ assuming\ a\ capture\ rate\ of\ 95\ \%$
- $e_{t_{CO_2}} = emissions\ from\ transport\ of\ CO_2$
- $e_{s_{CO_2}} = emissions\ from\ CO_2 storage$
- $e_{t_{CO_2}} + e_{s_{CO_2}} = 0.572\ \mathrm{kg}\ CO_2\ eq./\ \mathrm{kgH_2}\ ^2$
- $e_{CCU/S} = net\ emission\ savings\ from\ CO_2\ capturing$

1: According to EC (2024) Annex on Directive (EU) 2024/1788 | 2: Based on Solomon et al. (2024) and own assumptions (0.5 % CO_2 leakage)

Regulatory framework on EU level: Hydrogen production

Hydrogen production with a CO_2 capture rate of 95 % could satisfy regulatory requirements

Emissions from low-carbon hydrogen (incl. subsequent CO_2 transport and storage)[1]



Interpretation

- The diagram illustrates CO_2 emissions from low-carbon hydrogen production, including CO_2 emissions from compression for transport, storage and leakage. The standard requirement for upstream emissions also entails a methane leakage to be assumed[2].
- Under the assumed parameters, hydrogen production from natural gas meets the requirements of ~3.4 kg CO_2 eq./kg H_2 specified in the drafted Delegated Act.
- Conversely, for the given parameterization, the capture rate would have to be at least 88 % to meet the threshold. Lower capture rates increase uncaptured process emissions.
- However, emissions of ~2.8 kg CO_2 eq./kg H_2 remain. In this case, low-carbon hydrogen cannot be considered climate neutral.

1: Own calculation based on the methodology presented on the previous slide | 2: By 2027, a delegated act supplementing Regulation (EU) 2024/1787 could be presented with the method for calculating the methane intensity of crude oil, natural gas and coal extraction. As a result, the upstream and midstream emissions calculation might be affected.

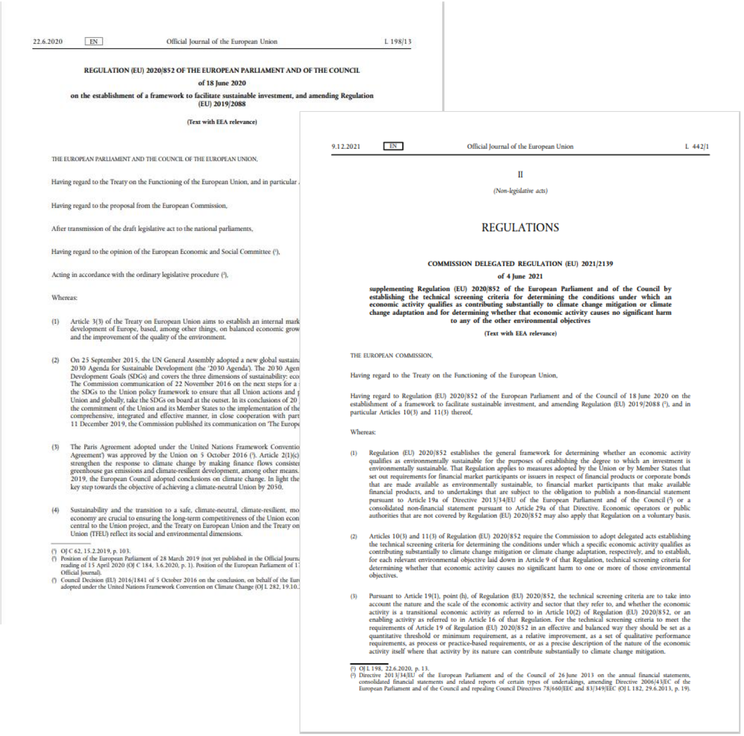
Regulatory framework on EU level: Hydrogen production

The EU Taxonomy is a classification system to evaluate environmental sustainability

Regulation 2020/852 and the associated Delegated regulation

- The EU taxonomy is a regulation (2020/852) that entered into force on 12 July 2020 and is a classification system defining criteria for economic activities to be considered as environmentally sustainable. These are the main criteria:
  - General conditions to be fulfilled (Article 3): i. contributing to at least one of the six targets defined in Article 9, ii. doing no significant harm to any other of these targets, iii. carried out in compliance with the minimum safeguards (Article 18), iv. compliance with technical screening criteria
  - An economic activity has to contribute to one of these 6 targets (Article 9):
    1. Climate change mitigation
    2. Climate change adaptation
    3. Sustainable use and protection of water and marine resources
    4. Transition to a circular economy
    5. Pollution prevention and control
    6. Protection and restoration of biodiversity and ecosystems
- The main target of this regulation is to direct private investments towards environmentally sustainable economic activities. There is a reporting obligation for large companies[3]: the Corporate Sustainability Reporting Directive (CSRD).

Documents[1,2]


22.6.2020 EN Official Journal of the European Union L 198/13

REGULATION (EU) 2020/852 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL

of 18 June 2020

on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088

(Text with EEA relevance)

9.12.2021 EN Official Journal of the European Union L 442/1

II

(Non-legislative acts)

REGULATIONS

COMMISSION DELEGATED REGULATION (EU) 2021/2139

of 4 June 2021

1: EC (2020) Regulation (EU) 2020/852 | 2: EC (2021) Delegated Regulation (EU) 2021/2139 | 3: Balance sheet total of at least 20 million euros, net sales of at least 40 million euros or at least 250 employees

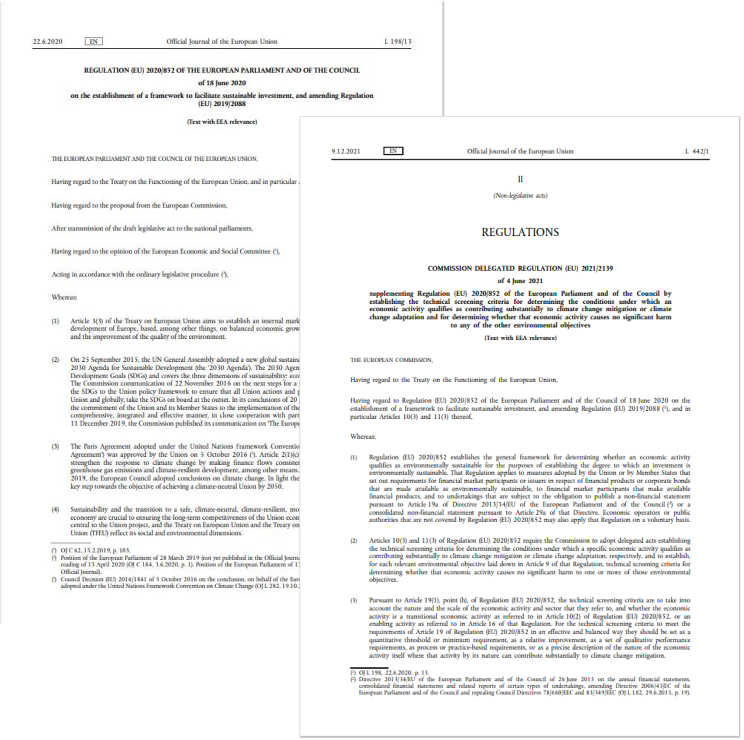
Regulatory framework on EU level: Hydrogen production

Emission reduction requirements for low-carbon hydrogen are higher in the EU Taxonomy

Application of the EU Taxonomy to low-carbon hydrogen projects

- Hydrogen and hydrogen-based synthetic fuels are compared to a fossil fuel comparator of 94 gCO_2 eq./MJ.
- For low-carbon hydrogen production to be acknowledged as environmentally sustainable under EU Taxonomy, the following technical screening criteria must be fulfilled (EU taxonomy delegated regulation 2021/2139):
  - **73.4** % of life-cycle GHG emission savings (corresponding to an upper GHG limit of 3 t CO_2 eq./t H_2). This value is higher than the value defined in the Delegated Act on low-carbon fuels (70%), hence, the EU taxonomy‘s criteria for hydrogen to be classified as sustainable is slightly stricter.
  - 70 % for hydrogen-based synthetic fuels (corresponding to an upper GHG limit of 28.2 g CO_2 eq./MJ).
- Further criteria regarding CO_2 transportation and storage (Delegated Regulation 2021/2139, 5.11 & 5.12):
  - CO_2 leakages during transportation from capture to injection point must not exceed 0.5 % of mass transported.
  - appropriate leak detection systems and monitoring plan, robust climate risk and vulnerability assessment.
- The criteria formulated by the EU taxonomy partly form a prerequisite for funding programs, e.g. on the German[3] and European level[4].

Documents[1,2]


22.6.2020 EN Official Journal of the European Union L 198/13

REGULATION (EU) 2020/852 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088

(Text with EEA relevance)

9.12.2021 EN Official Journal of the European Union L 442/1

II (Non-legislative acts)

REGULATIONS

COMMISSION DELEGATED REGULATION (EU) 2021/2139 of 4 June 2021 supplementing Regulation (EU) 2020/852 of the European Parliament and of the Council by establishing the technical screening criteria for determining the conditions under which an economic activity qualifies as contributing substantially to climate change mitigation or climate change adaptation and for determining whether that economic activity causes no significant harm to any of the other environmental objectives

(Text with EEA relevance)

1: EC (2020) Regulation (EU) 2020/852 | 2: EC (2021) Delegated Regulation (EU) 2021/2139 | 3: KfW IPEX-Bank (2024) | 4: European Investment Bank (2024)

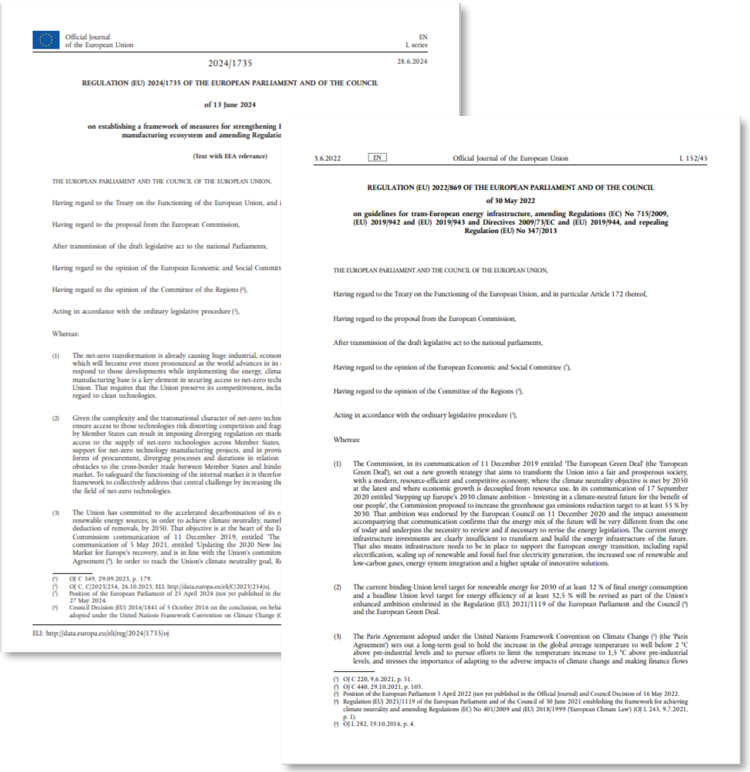
Regulatory framework on EU level: Infrastructure

Construction of CO_2 infrastructure is facing regulatory challenges and uncertainties

CO_2 infrastructure is promoted in the Net-zero Industry Act and TEN-E Regulation

- Low-carbon hydrogen requires the same infrastructure as green hydrogen, which is yet to be developed. The regulatory framework on hydrogen transport on the EU level is limited, but the hydrogen and gas decarbonization package provides for exemptions to the general unbundling rules to allow cross-subsidies between sectors[1]. Some EU Member states have developed a mechanism to facilitate the financing of hydrogen networks. Additionally, the European Hydrogen Backbone is a private initiative of European infrastructure operators to coordinate the hydrogen infrastructure ramp-up.
- For a functioning low-carbon hydrogen market, not only H_2 requires transport, but also CO_2 has to be transported to a storage site. As part of the Net-zero Industry Act (Regulation (EU) 2024/1735)[2], the EU commission has emphasized the importance of establishing a robust CO_2 transport & storage infrastructure but focusing on hard-to-abate emissions from the industry sector. It envisions the development of a fair, open, and non-discriminatory CO_2 market with cross-border networks and an EU-wide target of 50 million tonnes of annual CO_2 injection capacity by 2030.
- So far, there exist no specific unbundling rules for CO_2 networks, but the Trans-European Energy Infrastructure Regulation (TEN-E)[3] promotes open and non-discriminatory access to CO_2 infrastructure.
- The 2009 amendment of the London protocol would allow offshore CO_2 transport and storage in the EU. It is ratified by ten countries but it requires ratification by 36 countries to become legally binding[4].

Documents[2,3]


Official Journal of the European Union EN L series
2024/1735 28.6.2024
REGULATION (EU) 2024/1735 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL
of 13 June 2024

3.6.2022 EN Official Journal of the European Union L 152/45
REGULATION (EU) 2022/869 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL
of 30 May 2022
on guidelines for trans-European energy infrastructure, amending Regulations (EC) No 715/2009, (EU) 2019/942 and (EU) 2019/943 and Directives 2009/73/EC and (EU) 2019/944, and repealing Regulation (EU) No 347/2013

1: ACER (2024) European hydrogen markets | 2: EU (2024) Regulation (EU) 2024/17335 | 3: EU (2022) Regulation (EU) 2022/869 | 4: Resolution LP.3(4) Protocol to the convention on the prevention of marine pollution by dumping of wastes and other matter

The CO_2 infrastructure ramp-up

The challenges for CO_2 infrastructure development resemble those for hydrogen

Challenges for CO_2 infrastructure

High uncertainty about the regulatory framework for infrastructure
- Investors face high commercial risk while there is no clarity on the targeted role of low-carbon hydrogen.
- Information is missing on potential unbundling regulations in the CO_2 market.

The „Chicken-egg-rooster problem“
- Simultaneous development of CO_2 infrastructure, supply and demand may lead to coordination issues among market stakeholders.
- Investments in production and infrastructure may be unavailing if low-carbon hydrogen is only a bridging technology in the hydrogen market ramp-up.

Long time horizon for CO_2 infrastructure planning and construction
- Long development periods contradict with the short-term role of low-carbon hydrogen.
- Pipelines might be used not only for CO_2 from the production of low-carbon hydrogen in the short-term, but also for hard-to-abate CO_2 in the long-term.

Background

- The development of CO_2 infrastructure is essential to enable the feasibility of low-carbon hydrogen, as well as other applications in the hard-to-abate industries that rely on CO_2 transport and storage.
- At present, there is no public CO_2 infrastructure in place in the EU; only privately operated pipelines exist.
- Similar to hydrogen, CO_2 infrastructure is a critical component for building a functioning CO_2 economy. Without such infrastructure, investments in storage sites or the upgrading of CO_2 capture facilities are not economically viable.
- Both the European Union and the German federal government are addressing this through regulatory and strategic initiatives.

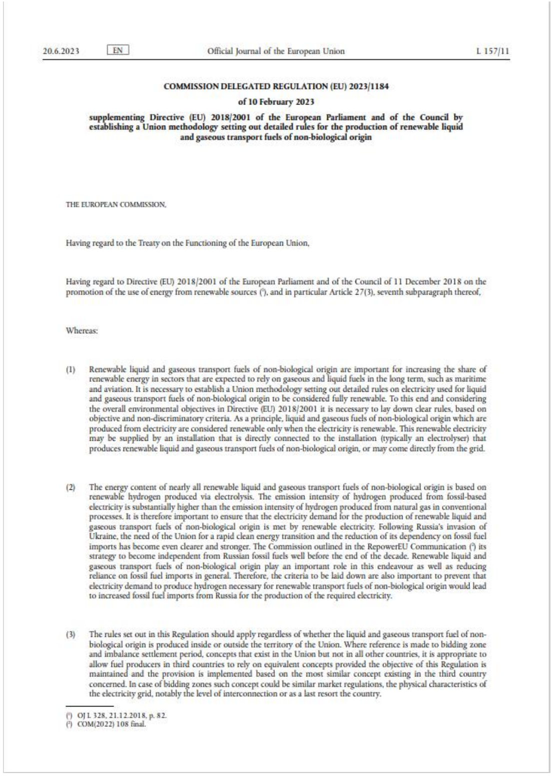
Regulatory framework on EU level: Hydrogen demand

There are no explicit regulatory targets for low-carbon hydrogen

End use targets for low-carbon hydrogen in EU regulation

- The EU targets to reduce net greenhouse gas emissions by 55 % in 2030, by 90 % in 2040 and to achieve climate neutrality by 2050[1]. The ReFuelEU Aviation initiaitve and the FuelEU Maritime initiative set targets for the reduction of emissions and the share of synthetic aviation fuels[2]. Low-carbon hydrogen can contribute to reach these targets.
- The Emissions Trading Scheme (ETS)[3] covers emissions from electricity and heat generation, industrial manufacturing, aviation and maritime sectors. The ETS2 is a separate system to advance emission reductions in the buildings, road transport and additional sectors. The Carbon Border Adjustment Mechanism (CBAM) Regulation[4] aims at promoting the competitiveness of low-carbon products by regulating the carbon emissions emitted during the production of imported and EU-made products. Both the carbon emission prices and the CBAM regulations may provide market incentives to promote the use of low-carbon hydrogen in the end use sectors.
- Low-carbon hydrogen is not considered as an RFNBO (Renewable Fuel of Non-Biological origin). RFNBOs are liquid and gaseous fuels, the energy content of which is derived from renewable sources other than biomass. RED III[5] includes specific targets for the use of RFNBOs for the industry and transport sector. Low-carbon hydrogen cannot contribute to reaching these targets. Additionally, the REPowerEU plan targets the consumption of 20 Mt of green hydrogen by 2030, focusing only on renewable hydrogen.[6]

Document[5]



20.6.2023 EN Official Journal of the European Union L 157/11

COMMISSION DELEGATED REGULATION (EU) 2023/1184

of 10 February 2023

supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin

THE EUROPEAN COMMISSION,

Having regard to the Treaty on the Functioning of the European Union,

Having regard to Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (1), and in particular Article 27(3), seventh subparagraph thereof,

Whereas:

(1) Renewable liquid and gaseous transport fuels of non-biological origin are important for increasing the share of renewable energy in sectors that are expected to rely on gaseous and liquid fuels in the long term, such as maritime and aviation. It is necessary to establish a Union methodology setting out detailed rules on electricity used for liquid and gaseous transport fuels of non-biological origin to be considered fully renewable. To this end and considering the overall environmental objectives in Directive (EU) 2018/2001 it is necessary to lay down clear rules, based on objective and non-discriminatory criteria. As a principle, liquid and gaseous fuels of non-biological origin which are produced from electricity are considered renewable only when the electricity is renewable. This renewable electricity may be supplied by an installation that is directly connected to the installation (typically an electrolyser) that produces renewable liquid and gaseous transport fuels of non-biological origin, or may come directly from the grid.

(2) The energy content of nearly all renewable liquid and gaseous transport fuels of non-biological origin is based on renewable hydrogen produced via electrolysis. The emission intensity of hydrogen produced from fossil-based electricity is substantially higher than the emission intensity of hydrogen produced from natural gas in conventional processes. It is therefore important to ensure that the electricity demand for the production of renewable liquid and gaseous transport fuels of non-biological origin is met by renewable electricity. Following Russia's invasion of Ukraine, the need of the Union for a rapid clean energy transition and the reduction of its dependency on fossil fuel imports has become even clearer and stronger. The Commission outlined in the RepowerEU Communication (2) its strategy to become independent from Russian fossil fuels well before the end of the decade. Renewable liquid and gaseous transport fuels of non-biological origin play an important role in this endeavour as well as reducing reliance on fossil fuel imports in general. Therefore, the criteria to be laid down are also important to prevent that electricity demand to produce hydrogen necessary for renewable transport fuels of non-biological origin would lead to increased fossil fuel imports from Russia for the production of the required electricity.

(3) The rules set out in this Regulation should apply regardless of whether the liquid and gaseous transport fuel of non-biological origin is produced inside or outside the territory of the Union. Where reference is made to bidding zone and imbalance settlement period, concepts that exist in the Union but not in all other countries, it is appropriate to allow fuel producers in third countries to rely on equivalent concepts provided the objective of this Regulation is maintained and the provision is implemented based on the most similar concept existing in the third country concerned. In case of bidding zones such concept could be similar market regulations, the physical characteristics of the electricity grid, notably the level of interconnection or as a last resort the country.

(1) OJ L 328, 21.12.2018, p. 82.
(2) COM(2022) 108 final.

1: EC (2024a) 2040 climate target | 2: ACER (2024) European hydrogen markets | 3: EC (2024b) EU Emissions Trading System | 4: EC (2023a) Regulation (EU) 2023/95 | 5: EU (2023b). Renewable Energy Directive (EU) 2023/1184 | 6: EC (2024c) REPowerEU

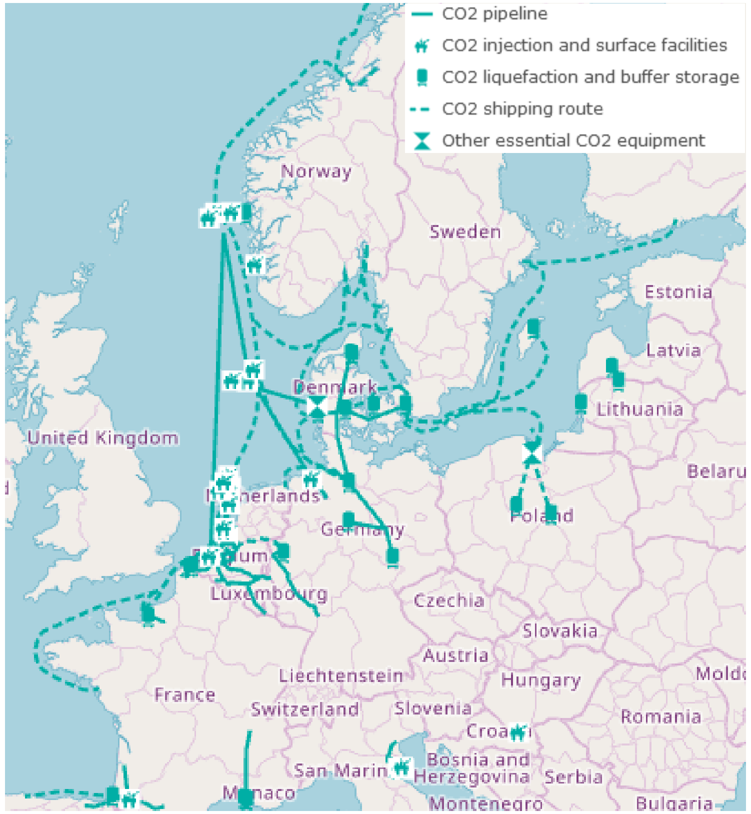
Regulatory framework on EU level: Hydrogen funding programs

EU PCI/PMI and IPCEI include low-carbon hydrogen projects

CO_2 infrastructure projects are considered Projects of Common Interest

- Most hydrogen support mechanisms at the EU level are classified as technology-neutral. Only some funding programs like the European Hydrogen Bank are not applicable for low-carbon hydrogen.[5]
- Projects of Common Interest (PCI) are infrastructure projects which have a significant impact on the EU electricity and gas systems and help the EU to achieve its energy policy and climate objectives. PCIs are eligible for funding from the Connecting Europe Facility (CEF).
- The 5th list of PCI (2021) included six CO_2 network projects[1]. The 1st list of PCI & PMI (2023) included 14 CO_2 network projects[2]. The map on the right shows the CO_2 network projects under consideration among the PCI/PMI list. The largest project EU2NSEA is designed to enable the transport and storage of CO_2 from North-West Europe to the North Sea in Norway and involves DK, FR, LV, LT, NL, PL, SE, CH, BE & DE. The offshore pipeline is planned to transport CO_2 from collection hubs in Belgium, France, the Netherlands and Germany to storage sites in the North Sea.
- The Important Projects of Common European Interest (IPCEI) are European projects in a key strategic value chain which consist of several company projects from various EU Member States. The project must prove that it follows an overriding European interest, and it would not be realized under market forces alone. IPCEI Hy2Use includes one project for production of low-carbon ammonia with natural gas and CCS in Norway.[3]

Map of CO_2 network PCI[4]



1: ACER (2024a) Projects of Common Interest | 2: EC (2023) Projects of common interest & Projects of mutual interest | 3: IPCEI Hydrogen (2024) | 4: EC (2024) PCI-PMI Transparency platform | 5: ACER (2024b) European hydrogen markets

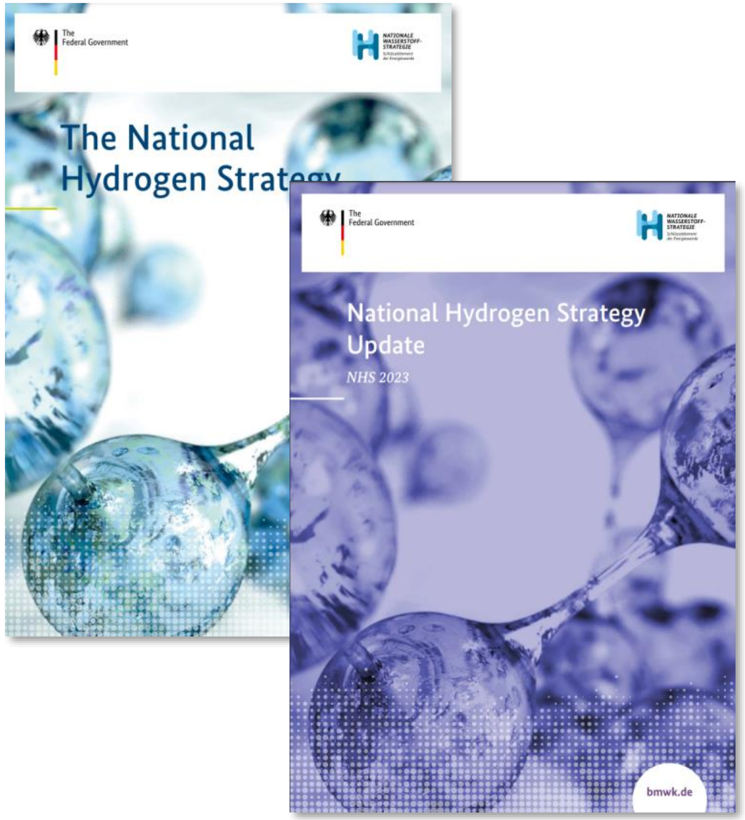
Regulatory framework in Germany: National Hydrogen Strategy

National hydrogen production is intended to be based on water electrolysis

Low-carbon hydrogen only plays an indirect role in the national hydrogen strategy

- The first national hydrogen strategy was published by the Federal Ministry of Economics and Technology in June 2020. About three years later, the Ministry formulated and published an update of the National Hydrogen Strategy.
- In the first document, the German government emphasized that it considers only green hydrogen to be sustainable in the long term and that it should be the focus of promotional activities. At the same time, it was expected that a global hydrogen market would be established on which low-carbon hydrogen would also be traded, which would play a role in Germany's import-dependent supply.
- The update of the strategy in 2023 continues to focus on the national supply of green hydrogen. However, unlike in the initial document, it is planned to promote the use of low-carbon hydrogen as a bridging technology if necessary and in line with emissions reduction targets. But further measures were announced that could pave the way for the use of low-carbon hydrogen, for example, a dialogue on transport and permanently safe CO_2 storage in the EU.
- Hydrogen production and supply are planned to be based on green hydrogen in the German hydrogen strategy. Low-carbon hydrogen might take on an ancillary role as a bridging technology.

Documents[1,2]



1: BMWi (2020) The National Hydrogen Strategy | 2: BMWK (2023) National Hydrogen Strategy Update

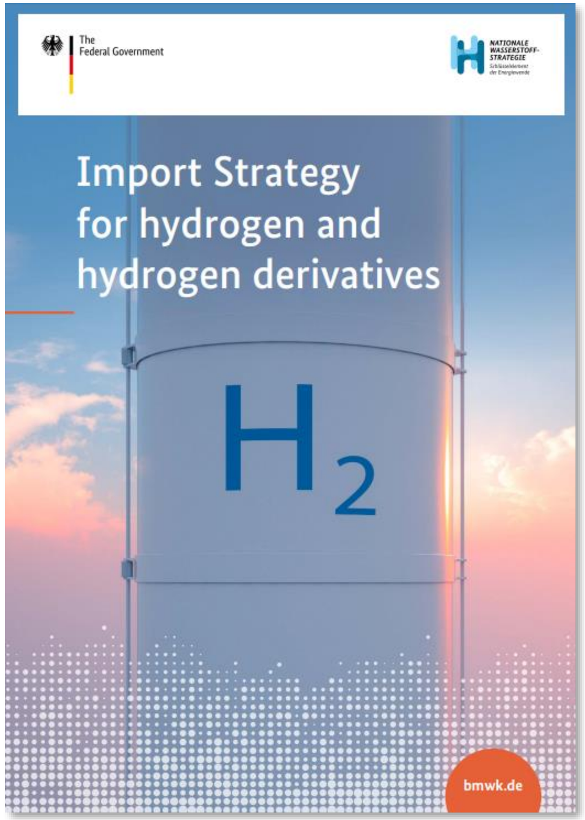
Regulatory framework in Germany: Import strategy

Low-carbon hydrogen may play an important role in supply through imports

Significant import shares and direct promotion of the use of low-carbon hydrogen

- The import strategy for hydrogen and hydrogen derivatives was published in July 2024 and is a supplement to the update of the National Hydrogen Strategy (NWS). The strategy is motivated by the expectation that a significant proportion of hydrogen supply must be imported to cover projected hydrogen demand. In 2030, the government expects an import share of 50-70 %.
- While the NWS still only calls for the direct promotion of green hydrogen, the import strategy also targets the use of low-carbon hydrogen. The idea is to create a reliable supply as quickly as possible. The prerequisite for this is that the hydrogen meets a threshold value of approx. 3.4 kg CO_2 eq. /kg H_2. This threshold is aligned with the value implied by the EU Internal Gas and Hydrogen Market Directive being discussed at EU level.
- With regard to domestic production of low-carbon hydrogen, the import strategy does not formulate any explicit statements, and therefore no deviating statements compared to other German strategies.

Documents[1]



1: BMWK (2024) The Import Strategy for hydrogen and hydrogen derivatives

Regulatory framework in Germany: Carbon Management Strategy

Carbon capture and storage is prohibited in DE - this could change

Relevant climate neutrality studies conclude that CCUS is vital for reaching climate neutrality

- In a report commissioned by the German government, relevant climate neutrality studies were examined with regard to the necessity of CCUS in general for reaching climate neutrality. The studies conclude that CO_2 must be captured and stored or reused in relevant quantities as early as 2030 and that the general use of CCS is essential for reaching climate neutrality targets[1,2].
- In this context, the German government formulated the key points for a carbon management strategy in a paper in February 2024[2]. In this paper, the government emphasizes the necessity of CCUS on the path to climate neutrality. CCUS should be promoted only to avoid emissions that are technically difficult or impossible to avoid. This is particularly the case for the lime and cement industries. Additionally, it could be applied in industrial processes where alternatives are not yet cost-effective. The production of hydrogen is not explicitly included in the strategy.
- The large-scale capture and storage of CO_2 is currently prohibited by law in Germany. In addition, following the London Protocol, CO_2 may not be exported for offshore storage, but this does not include the export for onshore storage. The CMS envisages the ratification of an amendment to the relevant article (6) of the London protocol[4] and the Carbon Dioxide Storage Act[3].
- Additionally, the strategy has formulated the intention to revise the legal framework such that the development of a CO_2 infrastructure in Germany becomes more accessible.

Document[2,3]

Bundesministerium für Wirtschaft und Klimaschutz

Eckpunkte der Bundesregierung für eine Carbon Management-Strategie

26. Februar 2024

Deutschland hat das Ziel, bis 2045 eines der ersten großen klimaneutralen Industrieländer zu sein. Dafür hat die Bundesregierung in den vergangenen zwei Jahren erhebliche Anstrengungen unternommen, etwa beim Ausbau der Erneuerbaren Energien, der Dekarbonisierung der Industrie, dem Hochlauf der Wasserstoffwirtschaft, dem Ausbau der E-Mobilität, der Stärkung des Emissionshandels, der Planungs- und Genehmigungsbeschleunigung und der Wärmewende im Gebäudesektor. Übergeordnetes Ziel ist die Vermeidung von Emissionen. Zentral ist und bleibt für den Klimaschutz die Dekarbonisierung, das heißt neben dem Kohleausstieg der Ausstieg aus fossilen Energien insgesamt.

Aus heutiger Sicht ist klar, dass auch das Abscheiden und Speichern und das Abscheiden und Nutzen von CO_2 (Carbon Capture and Storage – CCS und Carbon Capture and Utilization – CCU) einen Beitrag auf dem Weg zur Klimaneutralität leisten muss. Grund hierfür ist, dass Emissionen in bestimmten Bereichen nur schwer oder anderweitig nicht vermeidbar sind. In seinem neuesten Bericht geht auch der Weltklimarat (IPCC) davon aus, dass neben anderen Minderungsmaßnahmen auch CCS/CCU in emissionsintensiven Sektoren mit schwer vermeidbaren Emissionen eine notwendige Klimaschutztechnologie ist, um 1,5 Grad Temperaturerhöhung nicht zu überschreiten. Die Bundesregierung wird deshalb die Nutzung dieser Technologien ermöglichen. Die große Mehrheit wissenschaftlicher Studien zur Treibhausgasneutralität, die für den letzten Evaluierungsbericht zum Kohlendioxid-Speichergesetz (KSpG) der Bundesregierung (Bericht vom 22.12.2022, BT-Drs. 20/5145) ausgewertet wurden, kommt zu dem Schluss, dass bereits ab 2030 CO_2 in relevanten Mengen abgeschieden und gespeichert oder weitergenutzt werden muss, damit die Klimaneutralität bis 2045 erreichbar ist. Dies gilt insbesondere, aber nicht nur, für diejenigen Industrien, deren Emissionen schwer vermeidbar sind und die durch die Verteuerung der Zertifikate des Europäischen Emissionshandels zunehmend unter Kostendruck geraten – zum Beispiel die Zement- und Kalkindustrie, Bereiche der Grundstoffchemie und die Abfallverbrennung. Auch diese Branchen brauchen die Perspektive auf klimaneutrales Wirtschaften und eine gute Zukunft am Standort Deutschland.

Die Bundesregierung wird deshalb im Rahmen einer Carbon Management-Strategie die Grundlagen zur Nutzung dieser Technologien und zum Transport und der Speicherung von CO_2 schaffen. Nach einem breit angelegten Stakeholderdialog mit Vertreterinnen und Vertretern aus Zivil-

1

1: Deutscher Bundestag (2022) Evaluierungsbericht der Bundesregierung zum Kohlendioxid-Speicherungsgesetz | 2: BMWK (2024a) Eckpunkte der Bundesregierung für eine Carbon Management Strategie | 3: BMWK (2024b) Draft law of the Federal Government to amend the Carbon Dioxide Storage Act | 4: Resolution LP.3(4) (2009)

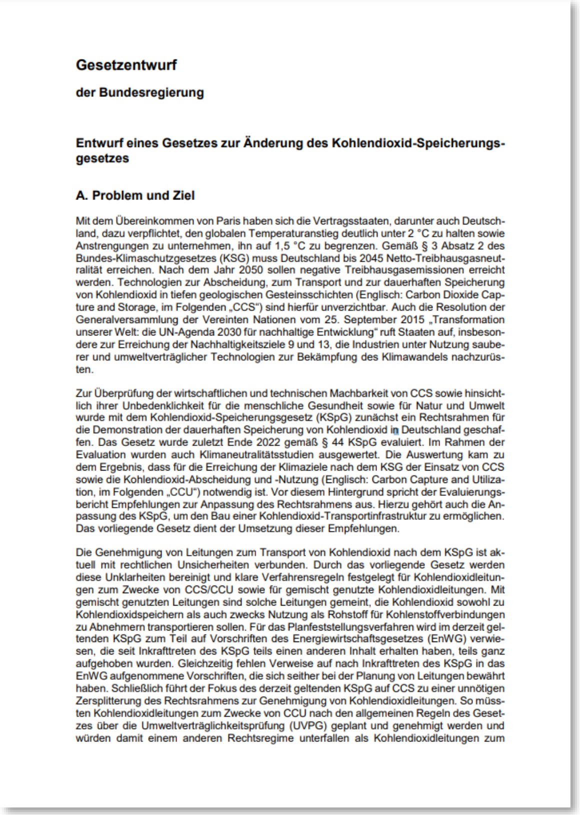
Regulatory framework in Germany: Carbon Dioxide Storage Act

Carbon transport and storage could be enabled under certain requirements

An amendment draft is available, the implementation is pending

- The draft of the Carbon Dioxide Storage Act amendment is intended to enable the offshore storage of CO_2 primarily in the area of the continental shelf and the external economic zone. Onshore storage is not to be permitted but can be enabled at state level. Storage in protected sea areas is prohibited, and special protective measures are prescribed for sensitive marine areas.
- Along with the need for CCUS, the German government's evaluation report also emphasized the need for CO_2 transport infrastructure. The draft is intended to adapt the legal framework to enable the development of a CO_2 transport infrastructure, for example by repurposing natural gas pipelines.
- This draft does not explicitly prohibit the capture and storage of CO_2 for the production of hydrogen, as it is the case for coal-fired power generation.
- According to the Carbon Management Strategy, outdated and missing references in the current Carbon Dioxide Storage Act to the Energy Industry Act lead to the failure of plan approval procedures of CO_2 pipelines. The German government intends to adjust the legal framework to harmonize the two laws.
- The extent to which this law will actually be amended remains uncertain at the time of this analysis. In the absence of this amendment, the production of low-carbon hydrogen from natural gas and the storage of CO_2 is currently not possible in Germany.

Document[3]



Gesetzentwurf

der Bundesregierung

Entwurf eines Gesetzes zur Änderung des Kohlendioxid-Speicherungsgesetzes

A. Problem und Ziel

Mit dem Übereinkommen von Paris haben sich die Vertragsstaaten, darunter auch Deutschland, dazu verpflichtet, den globalen Temperaturanstieg deutlich unter 2 °C zu halten sowie Anstrengungen zu unternehmen, ihn auf 1,5 °C zu begrenzen. Gemäß § 3 Absatz 2 des Bundes-Klimaschutzgesetzes (KSG) muss Deutschland bis 2045 Netto-Treibhausgasneutralität erreichen. Nach dem Jahr 2050 sollen negative Treibhausgasemissionen erreicht werden. Technologien zur Abscheidung, zum Transport und zur dauerhaften Speicherung von Kohlendioxid in tiefen geologischen Gesteinsschichten (Englisch: Carbon Dioxide Capture and Storage, im Folgenden „CCS") sind hierfür unverzichtbar. Auch die Resolution der Generalversammlung der Vereinten Nationen vom 25. September 2015 „Transformation unserer Welt: die UN-Agenda 2030 für nachhaltige Entwicklung" ruft Staaten auf, insbesondere zur Erreichung der Nachhaltigkeitsziele 9 und 13, die Industrien unter Nutzung sauberer und umweltverträglicher Technologien zur Bekämpfung des Klimawandels nachzurüsten.

Zur Überprüfung der wirtschaftlichen und technischen Machbarkeit von CCS sowie hinsichtlich ihrer Unbedenklichkeit für die menschliche Gesundheit sowie für Natur und Umwelt wurde mit dem Kohlendioxid-Speicherungsgesetz (KSpG) zunächst ein Rechtsrahmen für die Demonstration der dauerhaften Speicherung von Kohlendioxid in Deutschland geschaffen. Das Gesetz wurde zuletzt Ende 2022 gemäß § 44 KSpG evaluiert. Im Rahmen der Evaluation wurden auch Klimaneutralitätsstudien ausgewertet. Die Auswertung kam zu dem Ergebnis, dass für die Erreichung der Klimaziele nach dem KSG der Einsatz von CCS sowie die Kohlendioxid-Abscheidung und -Nutzung (Englisch: Carbon Capture and Utilization, im Folgenden „CCU") notwendig ist. Vor diesem Hintergrund spricht der Evaluierungsbericht Empfehlungen zur Anpassung des Rechtsrahmens aus. Hierzu gehört auch die Anpassung des KSpG, um den Bau einer Kohlendioxid-Transportinfrastruktur zu ermöglichen. Das vorliegende Gesetz dient der Umsetzung dieser Empfehlungen.

Die Genehmigung von Leitungen zum Transport von Kohlendioxid nach dem KSpG ist aktuell mit rechtlichen Unsicherheiten verbunden. Durch das vorliegende Gesetz werden diese Unklarheiten bereinigt und klare Verfahrensregeln festgelegt für Kohlendioxidleitungen zum Zwecke von CCS/CCU sowie für gemischt genutzte Kohlendioxidleitungen. Mit gemischt genutzten Leitungen sind solche Leitungen gemeint, die Kohlendioxid sowohl zu Kohlendioxidspeichern als auch zwecks Nutzung als Rohstoff für Kohlenstoffverbindungen zu Abnehmern transportieren sollen. Für das Planfeststellungsverfahren wird im derzeit geltenden KSpG zum Teil auf Vorschriften des Energiewirtschaftsgesetzes (EnWG) verwiesen, die seit Inkrafttreten des KSpG teils einen anderen Inhalt erhalten haben, teils ganz aufgehoben wurden. Gleichzeitig fehlen Verweise auf nach Inkrafttreten des KSpG in das EnWG aufgenommene Vorschriften, die sich seither bei der Planung von Leitungen bewährt haben. Schließlich führt der Fokus des derzeit geltenden KSpG auf CCS zu einer unnötigen Zersplitterung des Rechtsrahmens zur Genehmigung von Kohlendioxidleitungen. So müssten Kohlendioxidleitungen zum Zwecke von CCU nach den allgemeinen Regeln des Gesetzes über die Umweltverträglichkeitsprüfung (UVPG) geplant und genehmigt werden und würden damit einem anderen Rechtsregime unterfallen als Kohlendioxidleitungen zum

1: Deutscher Bundestag (2022) Evaluierungsbericht der Bundesregierung zum Kohlendioxid-Speicherungsgesetz | 2: BMWK (2024a) Eckpunkte der Bundesregierung für eine Carbon Management Strategie | 3: BMWK (2024b) Draft law of the Federal Government to amend the Carbon Dioxide Storage Act

Regulatory framework in Germany: Hydrogen demand

The use of low-carbon hydrogen is legally addressed and promoted for some applications

The use of low-carbon hydrogen is promoted for the electricity and heating sector

- In general, similar to the EU level, low-carbon hydrogen can be used to meet Germany's emission reduction targets in all sectors. Strategies in Germany on hydrogen production and import are focused on green hydrogen. However, there are a few regulatory instruments permitting the use of low-carbon hydrogen in different (end user) sectors.
- The German Power Plant Strategy plans to provide subsidies covering the difference between natural gas and hydrogen costs, including low-carbon hydrogen, for up to 800 full load hours per year[1]. The use of low-carbon hydrogen is additionally being discussed in the draft of the Power Plant Security Act[2]. The consultation document lists the subsidization of operating costs for electricity generation using low-carbon hydrogen in the form of carbon contracts for difference (CCfDs). The prerequisite for this is compliance with the requirements formulated by the Delegated Act at the EU level.
- CCfDs are a policy instrument designed to promote decarbonization in industries with high GHG emissions, such as steel, cement and chemicals by bridging the cost gap between low-carbon technologies and conventional ones. The government agrees to pay the difference between the actual carbon abatement costs and the current carbon price[3]. CCfDs are applicable for low-carbon hydrogen.
- According to the German Buildings Energy Act[4] of 2023, up to 65 % of the energy used to heat buildings must come from renewable energy sources until 2030. The threshold can also be met by using low-carbon hydrogen.

Documents[2,3]

1: Oxford Institute for Energy Studies (2024) Germany's hydrogen ambitions in late 2024 | 2: BMWK (2024) Kraftwerkssicherheitsgesetz - Konsultation | 3: Carbon contracts for Difference (2024) | 4: Gesetz zur Einsparung von Energie und zur Nutzung erneuerbaren Energien zur Wärme- und Kälteerzeugung in Gebäuden

Summary: Regulatory framework on EU level and in Germany

The applicable regulatory framework for CO_2 transport and storage in Germany is pending

		Legal framework	Regulatory framework	Policy targets	Market incentives (incl. funding)
Low-carbon H_2	Production & Import		▪ Announced: Delegated act for low-carbon fuels (70 % GHG emission reduction along entire value chain) ▪ Effective: EU taxonomy (73.4 % GHG emission reduction along entire value chain)	▪ No specific policy targets in REPowerEU and European hydrogen strategy ▪ No specific policy targets in Updated National hydrogen strategy and Hydrogen import strategy	▪ Eligible for funding, e.g. IPCEI status ▪ Potential access to funding programs through compliance with EU taxonomy
Low-carbon H_2	Transport & Storage	▪ Approved: National hydrogen core network (EnWG §112b)		▪ Announced: European hydrogen backbone (private initiative, not binding) ▪ Announced: National storage strategy	▪ Approved: mechanism for inter-temporal allocation of hydrogen network costs
Low-carbon H_2	End use	▪ Heating sector: applicable for Building Energy Act targets (GEG §71f)		▪ Not applicable for RED III quotas for RFNBOs ▪ Power plant strategy	▪ CO_2 prices of EU ETS1 and ETS2 ▪ Applicable for Carbon Contracts for Differences
CO_2	Transport	▪ Announced: amendment to KdSpG	▪ Emissions are balanced according to Delegated act for low-carbon fuels and EU taxonomy ▪ EU net-zero industry act	▪ Approved: EU net-zero industry act	▪ Eligible for funding, e.g. PCI/PMI status
CO_2	Storage	▪ Large-scale CO_2 storage currently not permitted ▪ Announced: amendment to KdSpG	▪ Emissions are balanced according to Delegated act for low-carbon fuels and EU taxonomy	▪ Approved: EU net-zero industry act	▪ Eligible for funding, e.g. PCI/PMI status

Color coding: EU level, National level (Germany)

Outlook: Regulatory framework on EU level and in Germany

Low-carbon hydrogen definition and CO_2 infrastructure regulation are in process

Status-Quo

- **Definition:** The EU has presented a draft definition of low-carbon hydrogen, which is not yet final. This analysis shows that under the given assumptions a capture rate of at least 88 % must be achieved for natural gas-based hydrogen to be considered low-carbon according to the EU's definition. However, this does not entail that low-carbon hydrogen is climate neutral, as residual emissions remain.
- **Production:** Low-carbon hydrogen is assumed to be a bridging technology in the hydrogen market ramp-up. There is no level playing field compared to green hydrogen in terms of regulation and policy support. There are no explicit policy targets for low-carbon hydrogen, unlike for green hydrogen. However, funding instruments generally support projects for low-carbon hydrogen and CO_2 infrastructure.
- **Transport:** The legal and regulatory framework for CO_2 infrastructure is less developed than for hydrogen infrastructure but is an important aspect of the usage of low-carbon.
- **End use:** The combination of strategic documents in Germany sets the focus on green hydrogen production. However, the German government considers low-carbon hydrogen to contribute to a rapid hydrogen market ramp-up required to achieve climate neutrality by 2045. Additionally, low-carbon hydrogen may be used to reach emission reduction targets. Usage in the buildings and electricity sectors is explicitly permitted in the German regulatory framework.

Work in progress

- The EU Delegated Act on low-carbon fuels is yet to be implemented.
- An EU-wide certification scheme for green and low-carbon hydrogen is yet to be defined.
- CO_2 storage is currently forbidden in Germany, so is the export for offshore storage.
- If low-carbon hydrogen is desired to support the hydrogen market ramp-up, investors and consumers need clarity on the legal and regulatory framework.

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