Wasserstoff Campus
Salzgitter


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Project GreenH$_2$SZ

Conceptualization of a feasible green hydrogen supply for the Salzgitter region within the context of the European hydrogen strategy

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Project GreenH$_2$SZ

The project “Konzeptionierung einer marktfähigen grünen Wasserstoffversorgung für die Region Salzgitter im Kontext der europäischen Wasserstoffstrategie” (Conceptualization of a feasible green hydrogen supply for the Salzgitter region within the context of the European hydrogen strategy, GreenH$_2$SZ) aims to achieve climate-neutral applications and processes in the industrial and transport sectors.

1. Task definition & motivation

The market ramp-up targets for green hydrogen in the “REPowerEU Plan” envisage a supply of 20 million tonnes in the European Union by 2030, whereby 10 million tonnes will be imported into the EU (European Commission 2022). The project therefore focuses on the development of short-term solutions for a sufficient green-hydrogen supply in Salzgitter by 2030. In addition to the steel industry in Salzgitter, other hydrogen consumers, such as rail transport in the region of southeast Lower Saxony, are being considered. In addition to the hydrogen production in Salzgitter and on the coast of Lower Saxony, international production sites, such as in Tunisia or in Australia, are being considered for future export scenarios to Europe in order to achieve the ramp-up of a feasible and low-cost hydrogen supply.

The report explains the methodology and assumptions behind the calculated production and import scenarios by 2030 and ties in with the core messages of the thesis paper already published (Fraunhofer IST 2022). In addition to the evaluation of the scenarios, the implementation options of a power-to-X plant in the Salzgitter area are considered in order to develop Salzgitter as a visible model region for a successful transformation of industry and society towards climate neutrality.

2. Methodology

2.1 Data sheets

In order to obtain an overview of the market-ready hydrogen technologies, a data-sheet collection has been compiled concerning the mode of operation and the performance parameters. The data sheets can be continuously updated and provide a sound basis for knowledge transfer. As an example, **Fig. 1** shows the data sheet for proton-exchange membrane electrolysis (PEM electrolysis).

2.2 H$_2$ scenarios for domestic production and imports in 2030

For the evaluation of the hydrogen supply from domestic production in Lower Saxony and initial large-scale imports up to 2030, the methodology and fundamental assumptions along the individual technologies and infrastructures of the value chain are presented below. The continuously increasing hydrogen demand of Salzgitter AG for its transformation project SALCOS® alone (up to around 250,000 tonnes per year by the end of the 2030s) makes it necessary for the industrial location of Salzgitter to be connected to the European hydrogen market via the planned hydrogen-pipeline network. The import scenarios focus on a gigawatt-scale sea transport of hydrogen, feasible by 2030, via the available infrastructures and technologies of

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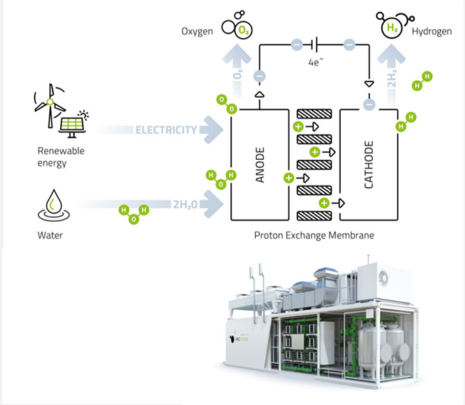
Operating principle

- Water is split into hydrogen and oxygen by applying a cell voltage
- Cell consisting of two noble metal-coated electrodes and a solid proton exchange membrane. Operation at ~70°C.
- Primary use and integration: steel industry, refineries, chemical and fuel production; Secondary use: grid services, local heat and oxygen supply

Technical characteristics

- Electrolyte: Acidic polymer membrane (H^+)
- Electrodes: PGM loading (Platin cathode, Iridium anode) ~3 g/kW$_{el}$
- System efficiency (LHV): ~61%$_{LHV}$ (55 kWh/kg$_{H2}$)
- Minimal space requirement, no electrolyte handling necessary
- System scalability: single modules from 0,1 MW$_{el}$ to systems of 10 MW$_{el}$
- Very dynamic operation, direct coupling to renewable electricity

Functional diagram & ME450 system



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the hydrogen transport media selected here: ammonia, methane, and methanol. The import terminal is assumed to be Wilhelmshaven, where project plans for hydrogen imports via ammonia and methane already exist (German Energy Agency 2022). The scenarios show the hydrogen-production prices and the resulting additional costs of the potential import chains, based on an electrolysis capacity of 1.5 GW available overseas and the quantity of hydrogen ultimately available in Salzgitter. The total cost include the cost elements of the complete import chain and take into account all conversion losses through to the offtake in Salzgitter.

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Fig. 1: Data sheet for PEM electrolysis technology, assumptions in accordance with (Clean Hydrogen Partnership 2022), image rights H-TEC SYSTEMS GmbH

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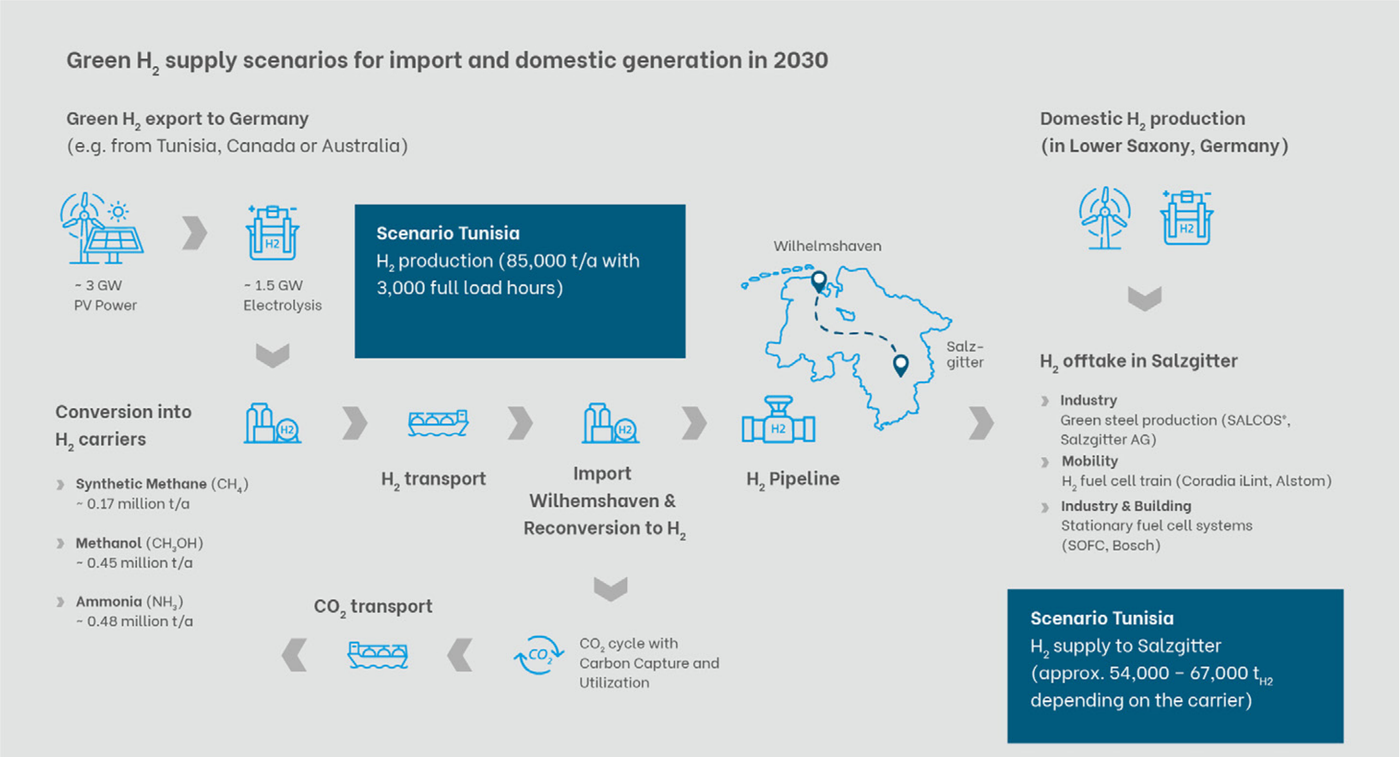
Fig. 2: Modeling of H_2 imports in 2030 with various transport media for H_2 offtake in Salzgitter in the Tunisia scenario



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2.2.1 Electrolysis

All scenarios are initially based on the calculation of regional hydrogen-production costs with the techno-economic assumptions of a scaled electrolysis plant in the capacity range up to several 100 MW in 2030. The development of automated electrolysis production sites with an annual production capacity in the gigawatt range, together with technological developments from the cell through to the system level, will lead to cost reductions for future electrolysis plants. As an example, cost reductions from 600 €/kW to 400 €/kW (alkaline electrolysis) and from 900 €/kW to 500 €/kW (PEM electrolysis) have been set as European targets for a 100 MW electrolysis in 2030 (Clean Hydrogen Partnership 2022). The hydrogen costs calculated here with low-temperature electrolyzers are based on a system-cost assumption of 470 €/kW and are considered over a period of 20 years with an interest rate of 8 %. The system efficiency is assumed to be 63 % LHV (approx. 53 kWh/kgH_2) over the entire stack lifetime.

Country- and region-specific generation scenarios differ as a result of the respective electricity generation potential from renewable energies.

2.2.2 Electricity from renewable energies – costs and availability

The country- and region-specific generation scenarios differ as a result of the respective electricity generation potential from renewable energies. The number of full-load hours of electrolysis as an indicator of the annual hydrogen production is based on the full-load hours of the renewable energies. The specific electricity production costs refer to the country-specific levelized cost of electricity (LCOE) without further additional costs, such as grid charges as the electricity purchase price for the electrolyzer.

For the calculation of potential production costs in Lower Saxony, the availability of onshore wind energy at good wind sites in Northern Germany with full load hours of 2,500 h/a is assumed. The average electricity production costs are assumed to be 55 €/MWh, based on today's costs (Kost et al. 2021). Excellent onshore wind sites (e. g. in Scandinavia or New Zealand) achieved LCOE of up to 35 €/MWh in 2020 (IRENA 2022c). Green hydrogen generation from offshore wind in the North Sea takes into account excellent sites with full load hours of 4,500 h/a. The lower limit of today's LCOE of offshore wind is given as 72 €/MWh (Kost et al. 2021), whereby the lowest weighted-average LCOE with 59 €/MWh (0.067 USD/kWh) was achieved in 2020 in the Netherlands, which is selected here for the offshore wind scenario (IRENA 2022b). The electrolysis full-load hours for hydrogen production in Germany are set equal to the full-load hours from the best onshore and offshore wind sites (2,500 and 4,500 h/h, respectively). Realized electrolysis plants can achieve higher utilization if additional electricity, e. g. from photovoltaic plants, is purchased via corresponding offtake agreements and guarantees of origin. In addition, the utilization can be further increased by means of an electricity storage system. A site-specific detailed engineering and dimensioning of an optimized plant design consisting of renewables, electricity and hydrogen buffer storage and the electrolysis and synthesis plant capacity was not within the scope of this project, but offers

Image source: iStock/hrui

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Fig. 3: Assumptions of electricity prices and full-load hours of electrolysis in the scenarios

a further cost reduction potential. The scenarios in Tunisia and Australia are predominantly based on electricity production using photovoltaics, whereby it is assumed that the installed capacity of the renewable energies is around twice as high as the nominal capacity of the electrolysis, so that a full-capacity utilization of up to 3,200 h/a is calculated. Electricity purchase costs are assumed to be 30 and 25 €/MWh for Tunisia and Australia, respectively, due to excellent solar irradiation, whereby many countries worldwide were able to achieve electricity production costs in the range of 32 - 49 €/MWh in 2020 (IRENA 2022c).

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Fig. 4: Comparison of hydrogen transport ships in use and required in the future. Abstract representation by ship length, assumptions from (Offshore Energy 2022), (Marine Insight 2022)

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20 million tonnes of climate-friendly hydrogen should be available in the EU in 2030. 10 million tonnes have to be imported.

2.2.3 Conversion into a hydrogen carrier medium for sea transport

In the export scenarios considered, the hydrogen from the electrolysis is converted into the respective liquid carrier medium in a downstream synthesis reactor. The capacity of the synthesis plant is designed for continuous-load operation (8000 h/a), utilizing an additional hydrogen pressure storage system with tanks and compressors as buffer storage. A further transport of the carrier medium to the export terminal is not included. Continuous transport by ship is made possible through further storage of the carrier medium at the export and import terminal.

2.2.4 Transport by ship

For the sea transport of hydrogen as ammonia, methane or methanol, there are terminals, infrastructures and transport ships available on the world market. **Fig. 4** provides an overview of the transport capacities of the available ships and the quantity of energy transported per vessel in relation to the respective medium. The world's only liquid-hydrogen ship "Suiso Frontier", which is in operation between Australia and Japan, shows that liquid hydrogen will not play an important role for hydrogen imports in 2030 due to the extremely low transport capacities. The shipping costs in the scenarios are based on a charter rate cost model for of a fleet that would be required for the specific hydrogen export volume. In all scenarios, the respective transport media are also used as the fuel for the hydrogen-transporting ships. It is therefore assumed that ammonia engines with similar efficiency values to those of already available methanol engines are deployable. A projected hydrogen market in accordance with the EU targets of 20 million tonnes by 2030 is thereby taken as a basis for the estimation the required terminal cost for export and import. In some cases, usable terminals are already available, in others they are yet to be built. This study is therefore based on an infrastructure corresponding to the market, which is used proportionally for the selected quantity of hydrogen. An infrastructure built and used separately for only one project would, in contrast, be significantly more expensive.

Applied vessel types – available today

Synthetic methane typical LNG carrier

- Length: 300 m
- Energy capacity: 1.00 TWh_{LHV}
- CH_4-tank: 174,000 m³

Ammonia largest carrier (in construction)

- Length: 230 m
- Energy capacity: 0.31 TWh_{LHV}
- NH_3-tank: 58,000 t

Methanol largest carrier

- Length: 186 m
- Energy capacity: 0.28 TWh_{LHV}
- CH_3OH-tank: 50,000 t

Liquid H_2 the world's only hydrogen vessel "Suiso Frontier"

- Length: 116 m
- Energy capacity: 0.003 TWh_{LHV}
- H_2-tank: 1,250 m³

LOHC largest „Ultra Large Crude Carrier"

- Length: 380 m
- Energy capacity: 0.91 TWh_{LHV} (Reference to H_2 storage quantity)[1]
- LOHC-tank: 440,000 t

Required vessel types

Equal to the carried energy of a typical LNG carrier

Synthetic methane typical LNG carrier

- Length: 300 m
- Energy capacity: 1.00 TWh_{LHV}
- CH_4-tank: 174,000 m³

Ammonia

- Estimated length: 330 m
- NH_3-tank: 190,000 t

Methanol

- Estimated length: 280 m
- CH_3OH-tank: 180,000 t

Liquid H_2

- Estimated length: 420 m
- H_2-quantity: approx. 30,000 t_{H2}
- H_2-tank: 420,000 m³

LOHC

- Estimated length: 400 m
- LOHC-tank: 500,000 t
- H_2-quantity: approx. 31,000 t_{H2}

[1] Dibenzyltoluol as LOHC with 6.2 t_{H2}/t_{LOHC}

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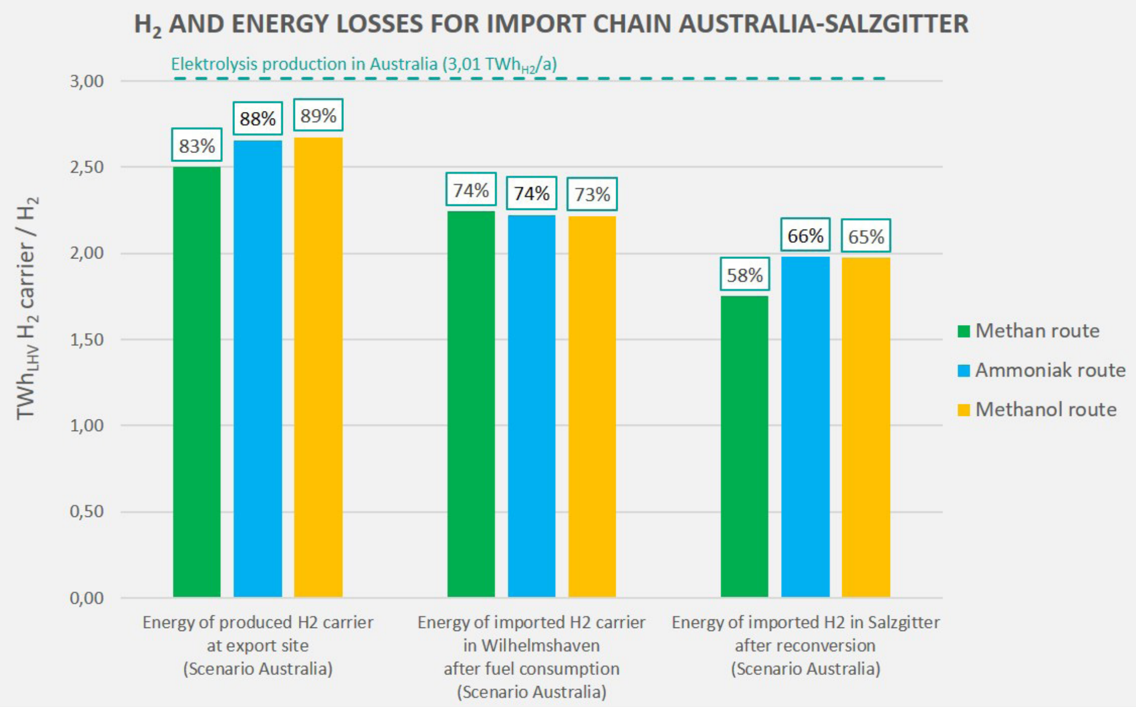
H_2 transport ships

Around 10 % of the global ammonia production is currently transported via pipelines or ships. For sea transport, gas tankers are deployed, which were primarily built for the transport of liquefied petroleum gas (LPG). By the end of 2019, around 170 of the more than 1,100 available LPG vessels were capable of transporting ammonia, with capacities ranging from 2,500 to 40,000 tNH3 (IRENA 2022a). The global liquefied natural gas shipping fleet increased by around 10 % year-on-year, with 641 LNG tankers were operational in April 2022, whereby newer vessels are almost exclusively built with a storage capacity of 150,000-180,000 m³ (IGU 2022). Today, the largest methanol tankers have a capacity of more than 40,000 tCH_3OH (Institute of Shipping Economics and Logistics (ISL) 2021). Similar to methanol, liquid organic hydrogen carriers (LOHC) can be used as an oil product using the available oil tankers. In the ultra-large crude carrier class, there are currently two operational oil tankers with a capacity of approximately 440,000 tonnes, which would nearly be equivalent to the amount of energy transported by an LNG vessel (Marine Insight 2022). In contrast, the only liquid-hydrogen vessel built to date by Kawasaki has a storage capacity of only 1,250 m³ for approx. 89 tH_2 (Kawasaki 2021).


H₂ AND ENERGY LOSSES FOR IMPORT CHAIN AUSTRALIA-SALZGITTER
Elektrolysis production in Australia (3,01 TWh_H2/a)
TWh_LHV H₂ carrier / H₂
3,00
2,50
2,00
1,50
1,00
0,50
0,00
83%
88%
89%
74%
74%
73%
58%
66%
65%
Energy of produced H2 carrier at export site (Scenario Australia)
Energy of imported H2 carrier in Wilhelmshaven after fuel consumption (Scenario Australia)
Energy of imported H2 in Salzgitter after reconversion (Scenario Australia)
Methan route
Ammoniak route
Methanol route

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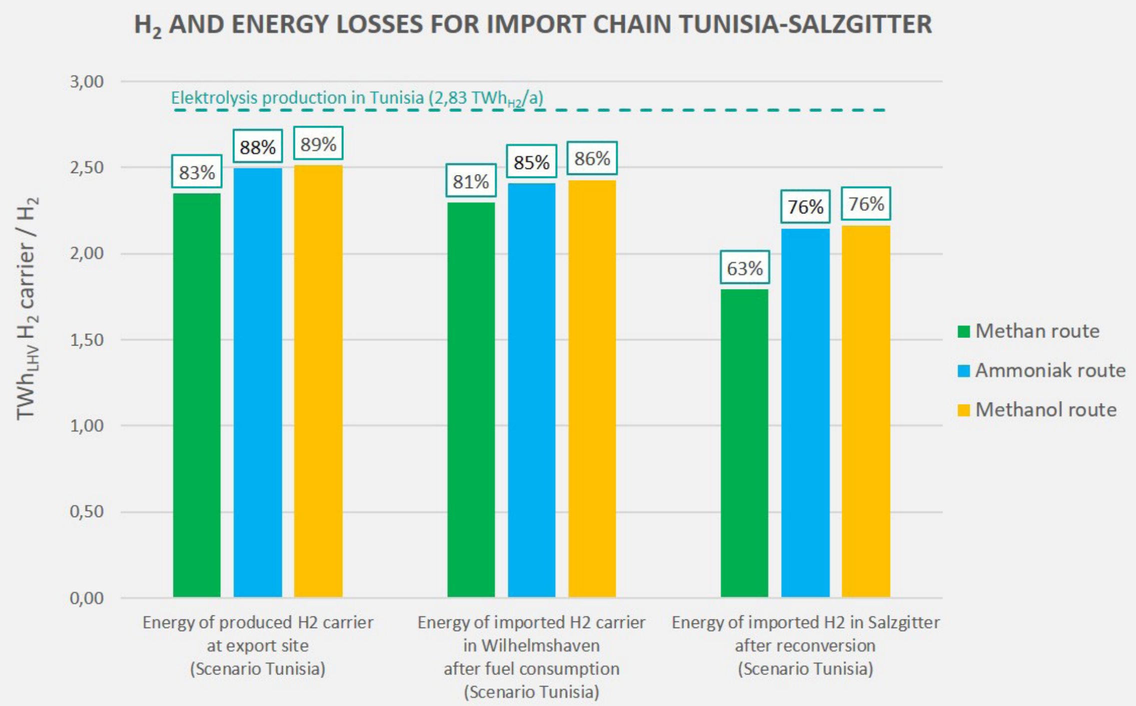
H₂ AND ENERGY LOSSES FOR IMPORT CHAIN TUNISIA-SALZGITTER
Elektrolysis production in Tunisia (2,83 TWh_H2/a)
TWh_LHV H₂ carrier / H₂
3,00
2,50
2,00
1,50
1,00
0,50
0,00
83%
88%
89%
81%
85%
86%
63%
76%
76%
Energy of produced H2 carrier at export site (Scenario Tunisia)
Energy of imported H2 carrier in Wilhelmshaven after fuel consumption (Scenario Tunisia)
Energy of imported H2 in Salzgitter after reconversion (Scenario Tunisia)
Methan route
Ammoniak route
Methanol route

6

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Fig. 5: Energy losses due to synthesis, ship fuel consumption and reconversion in the Australian scenario

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Fig. 6: Energy losses due to synthesis, ship fuel consumption and reconversion in the Tunisia scenario

The imported hydrogen volumes for industrial offtake in Salzgitter are calculated by the conversion efficiencies of the synthesis and reconversion process as well as the scenario-specific fuel consumption of the hydrogen carrier ships.

2.2.5 Reconversion for the provision of pure hydrogen

For hydrogen transport in Germany, a hydrogen-pipeline network is assumed, which connects electrolysis sites and import terminals on the North Sea coast with industrial hydrogen consumers such as in Salzgitter. For a uniform evaluation of the hydrogen supply, a reconversion of the carrier media at the import terminal in Wilhelmshaven is therefore considered.

For ammonia cracking for hydrogen recovery, a future cracking plant with a capacity of around 300,000 tH_2/a is modeled based on the assumptions of the plant design in the “H21 North of England” project (Sadler et al. 2018). The heat requirement for ammonia cracking is provided through combustion of the produced hydrogen-ammonia mix, enabling around 79 % of the imported hydrogen to be recovered. Ammonia crackers are commercially implemented today for small-scale applications (production < 700 tH_2/a), with few larger-scale plants having been realized so far (IRENA 2022a); as a result, the introduction of efficient ammonia crackers by 2030 is also subject to uncertainties. In general, there is very little literature available regarding large-scale ammonia cracking plants. A sufficient market maturity and energy efficient operation of GW-scale plants for dedicated hydrogen production has still to be proven.

Hydrogen recovery from methane is performed using autothermal reforming based on the design of an industrial plant for blue hydrogen production from natural gas (production approx. 300,000 tH_2/a) with a CO_2 capture of 94 % in the “H21 North of England” project (Sadler et al. 2018).

For the conversion of methanol into hydrogen, simplified assumptions regarding investment costs and CO_2 capture are applied with reference to autothermal reforming. Similar to ammonia cracking, methanol reformers for hydrogen production have not yet been realized at this plant size.

The total quantities of supplied hydrogen for offtake in Salzgitter are calculated using the energy losses during synthesis and reconversion (based on the LHV) as well as the distance-dependent fuel consumption of the hydrogen carrier ships in the scenarios (see **Figs. 5 and 6**). The influence of the transport distance is clearly visible in the comparison of Tunisia and Australia, especially for the ammonia and methanol routes. For these two routes, about 15 % of the electrolysis generation is consumed for transport between New South Wales (Port Kembla) and Wilhelmshaven (about 24,000 km), while less than 9 % is consumed for methane due to fewer trips. After import from Australia and reconversion at the terminal in Wilhelmshaven, a maximum of 66 % of the electrolysis generation is then available for further transmission to Salzgitter, while up to 76 % could be achieved for ammonia and methanol in the Tunisia scenario. The methane route always yields lower H_2 energy quantities after the reconversion step in Germany.

Image source: MAN

CO_2 transport ships

For the CO_2 export, the utilization of future CO_2 transport ships with a proposed capacity of more than 50,000 tonnes of CO_2 per cargo is assumed (Roussanaly et al. 2021). CO_2 has been transported by ship for more than 30 years, primarily in the food industry, although current ships are limited to a cargo capacity of around 1,000 tonnes of CO_2 (Element Energy 2018). For the Norwegian CCS project "Northern Lights", transport ships are currently being built with a capacity of 7,500 m^3 for a cargo of around 8,000 tonnes of CO_2 (Northern Lights 2022). The development of dual tankers that are suitable for transporting both LNG and liquid CO_2, for example, is a current topic of research projects (Datta et al. 2020). With such ships, empty voyages could be avoided.

LNG ships can transport green hydrogen as synthetic methane. An additional transport of CO_2 is required for this. A certification system must record the resulting greenhouse gas emissions of the entire transport chain and relate them to the delivered tonne of hydrogen.

The North Sea corridor, with electrolyzers and import terminals, is considered a central nucleus for the development of the European hydrogen network. At the Energy Hub Port of Wilhelmshaven, for example, GW-scale electrolysers, import terminals for ammonia and methane and hydrogen caverns are planned.

2.2.6 Transport to customer

The assumptions regarding hydrogen transport via pipeline are based on the development of the “European Hydrogen Backbone” as a vision of a Europe-wide hydrogen network driven by 32 energy infrastructure operators from 28 countries (EHB 2022). According to the hydrogen import target of 10 million tonnes in 2030 in the European Commission‘s REPowerEU program, a hydrogen network of 28,000 km in length is proposed for 2030 (European Commission 2022), (EHB 2022). The North Sea corridor is considered the central nucleus of the network development as the first hydrogen pipelines are to be built in the Netherlands, Belgium, and northwestern Germany in order to make imports available to industrial customers via the import terminals that already exist or are being built for liquefied natural gas and ammonia. The expansion will be carried out via, amongst other things, a number of IPCEI projects (“Important Projects of Common European Interest”), in which a pipeline connection to Salzgitter is planned. The costs assumed here for the transport from Wilhelmshaven to Salzgitter correspond to the assumptions of the long-distance-pipeline operators for a high utilization of the pipeline, as a result of which around 23.5 TWhH_2 (approx. 700,000 tH_2) per year will be transported through the pipeline.

2.2.7 CO_2 closed-loop system for methane and methanol

While the nitrogen for ammonia synthesis in the Haber-Bosch reactor can be provided on site via an air separation plant, the storage of hydrogen in methane and methanol is faced with the problem of climate-friendly carbon supply for the synthesis. In the example of hydrogen production of 85,000 tH_2/a with an electrolysis capacity of 1.5 GW, a CO_2 feed of around 465,000 tCO_2/a is required for methanation of the green hydrogen, while methanol production requires around 620,000 tCO_2/a. CO_2 air-capture technologies (direct air capture) are not expected to have achieved the required technological maturity to economically provide these amounts of CO_2 by 2030. A further option is CO_2 capture from bioenergy plants, such as biomass power plants. However, sufficient CO_2 supply from this alone will also be difficult to implement by 2030. In addition, CO_2 capture from biogenic sources should be used to meet the targets for negative emissions in the long term.

The CO_2 demand for the production of the hydrogen carrier medium is therefore covered in the scenarios through

CO_2 capture from industrial point sources with emissions that are difficult to avoid, such as in the cement industry. Plans for a CO_2 pipeline infrastructure in Germany outline an initial network between industrial sites and Wilhelmshaven with a length of 1,000 km for a transport volume of around 19 million tonnes of CO_2 per year (Open Grid Europe 2022), whereby CO_2 capture from industrial emissions in Germany is proposed in a magnitude of 15 million tCO_2/a to achieve climate neutrality in 2045 (German Energy Agency 2021). The CO_2 required at the hydrogen-production site will be exported from Germany by ship. After the hydrogen import, CO_2 will be captured again directly at the port during the reforming process of methane or methanol to feed the pure hydrogen into the dedicated hydrogen pipeline network. Assuming a highly efficient carbon capture & utilization (CCU) technology, around 94 % of the annual CO_2 requirement for the hydrogen import scenarios can therefore be managed by a CO_2-transport system, whilst around 6 % of the annual CO_2 demand must be added annually from industrial point sources. In the methane scenario, these uncaptured CO_2 emissions would cause greenhouse gas emissions of about 0.5 tonnes of CO_2 per tonne of hydrogen supplied to industrial offtake in Salzgitter.

If it is possible to provide the required CO_2 from “green” sources, e. g. by advanced DAC plants in the long term, the

700,000 t H_2 transport volume - Delivers a medium 4.7 GW H_2 pipeline per year. This amount of H_2 would need to be delivered by around 100 ammonia ships including subsequent cracking. Via the methane pathway, around 30 deliveries would be required.

Image source: Adobe Stock/nordseefoto

remaining GHG emissions can be further reduced until there is only "green" CO_2 in the cycle.

2.2.8 Calculation of the total costs

All cost components of the import scenarios always refer to the amount of hydrogen supplied for offtake in Salzgitter, which reaches a proportion of 58 % and 76 % of the hydrogen production at the electrolyzer site (see **Figs. 5 and 6**). Through the assumptions for the reconversion of all transport media, a uniform hydrogen price is obtained, which can be compared with the costs of a regional hydrogen production in Northern Germany. Alternatively, the hydrogen carrier media can be used in various applications and industrial sectors without reconversion, which, however, does not allow for a comparison for a dedicated pure hydrogen demand. For example, methanol and ammonia based on green hydrogen can be directly processed in the chemical or fertilizer industry, whereas methane can be used in current natural-gas applications or iron-ore direct-reduction plants with a corresponding CO_2 capture.

3. Results and discussion

3.1 H_2 production in Lower Saxony compared to import scenarios, using Tunisia and Australia as examples

Hydrogen production in Northern Germany can achieve the most favorable supply costs of around 4 €/kgH_2 in 2030 through the use of onshore and offshore wind resources. The import scenarios Tunisia and Australia achieve costs of around 4.83 to 5.45 €/kgH_2 with the ammonia route. The additional costs for conversions and transport cannot undercut the difference between the more favorable production costs in Tunisia (2.58 €/kgH_2) or Australia (2.25 €/kgH_2) and production in Germany. Assuming a high utilization of the hydrogen pipeline, the transport costs within Germany (< 0.10 €/kgH_2) to Salzgitter are negligible, while potential pipeline network fees are not included.

The results clearly show that the costs for conversion and reconversion of the hydrogen as well as the costs due to losses incurred in the process are the largest cost drivers in addition to the actual production.

With appropriate utilization, the costs of the infrastructure per kilogram of hydrogen are low for short and medium distances. The new construction of terminals, pipelines and dedicated carrier vessels with hydrogen-carrier-based propulsion systems, however, causes enormous investments and requires a significant amount of time for planning, approval and realization. Despite the comparatively higher costs, transport via methane is advantageous in this respect, as the majority of the infrastructure already exists (see chapter 3.2).

Scenario Tunisia

In the comparison of the hydrogen carrier media, ammonia achieves the highest cost efficiency. The hydrogen losses accounts to approx. 24 % of the hydrogen generation abroad, which is mainly due to the heat supply for the ammonia splitting. Methane and methanol can respectively supply 63 % and 76 % of the electrolysis generation to Salzgitter in the Tunisia scenario. The shipping

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Fig. 7: Costs of hydrogen imports from Tunisia compared to production in Lower Saxony in 2030

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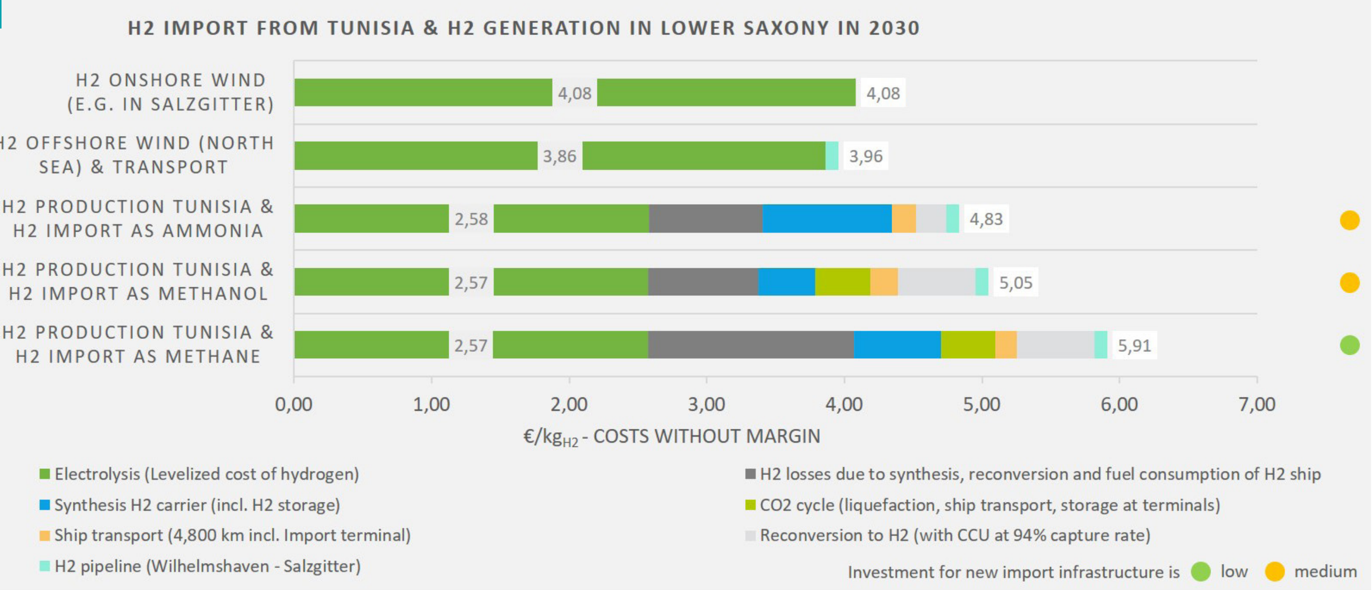

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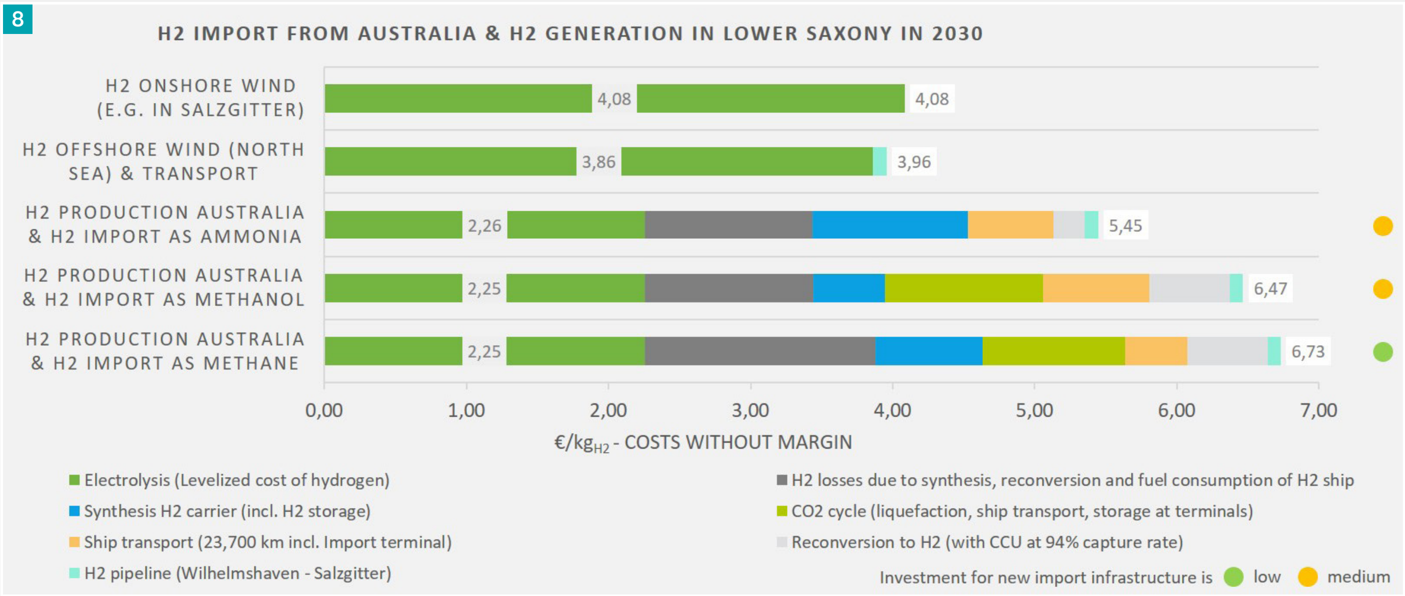

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Fig. 8: Costs of hydrogen imports from Australia compared to production in Lower Saxony in 2030

costs for the relatively short distance account to below 5 % of the total costs for all hydrogen carriers, while the CO_2 transport system is below 8 %.

Scenario Australia

The Australia scenario shows the impact of the longer transport distance on total costs with the route from southeast Australia (New South Wales) to Wilhelmshaven, with a round-trip time of up to 78 days depending on the ship type. Hydrogen transport increases to a cost proportion of 7 % (methane), 12 % (methanol) and 17 % (ammonia), while the CO_2 loop also increases to up to 17 % of the total cost. As a result, the CO_2 supply price doubles to up to 100 €/tCO_2. In addition to reducing fuel consumption and specific greenhouse gas emissions, the introduction of multi-modal transport ships for storing the liquid CO_2 and the hydrogen carrier – which are not yet available today – would therefore be a decisive milestone in the development of these import scenarios.

The final hydrogen supply is reduced to 58 % (methane), 65 % (methanol), and 66 % (ammonia) of the production in Australia, resulting in higher overall hydrogen costs compared to the Tunisia scenario.

Electrolyzers in Northern Germany can achieve the lowest green hydrogen supply costs of around €4/kgH_2 in 2030 compared to international import scenarios from overseas. Ammonia achieves the lowest import costs.

3.2 Estimation of market maturity and technological availability for the realization of H_2 import chains by 2030

In addition to the techno-economic assessment of the various supply scenarios via the individual transport media, **Fig. 9** provides an estimation of the technological maturity and the resilience and/or quality of the available data on the respective elements of the import chain options. The evaluation system also thereby takes into account the investment required for any new construction of the necessary infrastructures for import volumes on a gigawatt scale by 2030. For LOHC and especially liquid hydrogen, comparatively greater risks or lower market maturity still exist for timely realization. The major risk for the carbon-based routes via methanol and methane is the lack of a regulatory legal basis for CO_2 storage and subsequent export to other countries, as well as for high investments for the development of the CCU infrastructure.

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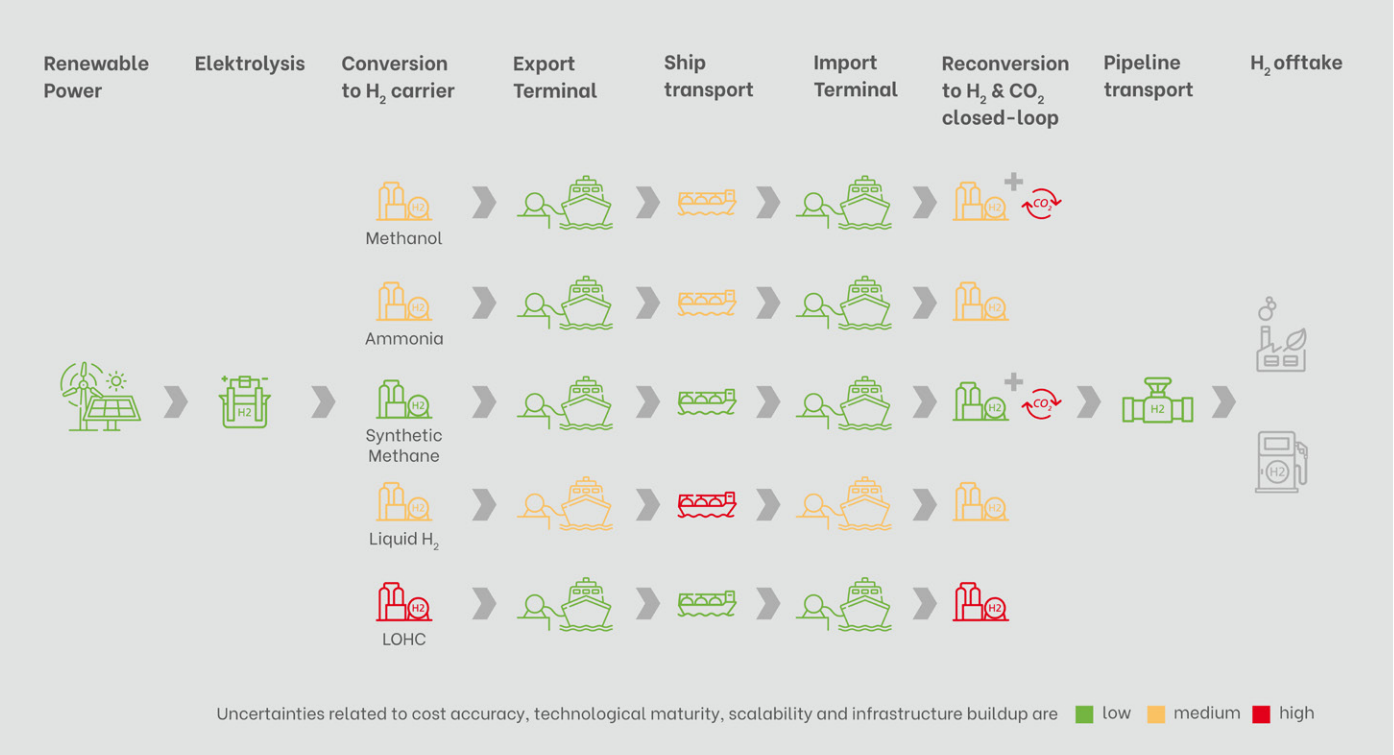
Fig. 9: Technological maturity and market availability of the respective technologies and infrastructure for future hydrogen supply chains up to 2030



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Bildquelle: Wasserstoff Campus Salzgitter

The demonstrator from the Wasserstoff Campus Salzgitter is used for trainings and knowledge transfer.

3.3 Interactive demonstrator for the scenarios

For the visualization and explanation of the regional hydrogen production and the imports shown for 2030, an interactive demonstrator has been developed for the presentation and modeling of the scenarios. Together with the exhibition “Energiewende Niedersachsen” (Energy transition Lower Saxony), the demonstrator from the Wasserstoff Campus Salzgitter serves to convey the knowledge from the project results. By means of various presentation modes, the demonstrator presents the different technologies and pathways of the entire value chain. Interactive sliders emphasize the importance and influence of the electricity price, the electrolysis costs and further parameters on the achieved total price of hydrogen.

3.4 Project development for hydrogen production in the Salzgitter metropolitan area

The project also investigated how specific projects for generation can be developed in the Salzgitter region and where potential customers for the hydrogen may be available. Decisive factors hereby are suitable locations and the prospect of long-term economic operation.

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Fig. 10: Interactive demonstrator for the hydrogen supply scenarios

3.4.1 Location conditions and possible scenarios

The choice of location for a hydrogen production plant depends on various criteria. These include the availability of:

- Electrical energy
- Water
- Customers for the hydrogen
- Optional customers for the by-products oxygen and waste heat

In the case of the further conversion of the hydrogen into synthetic methane, CO_2 is also additionally required.
The integration of all these factors at one suitable location is a complex challenge and is also referred to as industrial symbiosis on account of the typically different partners involved. Due to the comparatively high cost of electricity in Germany, the implementation of this symbiosis is, however, desirable in order to make the best possible use of electricity as a valuable energy source. In the following, the individual factors are explained in more detail and their feasibility within the framework of this project is evaluated.

Electrical energy

Electrical energy is required in electrolysis in order to split water into its components of hydrogen and oxygen. In contrast to the modeling above, an electrolysis capacity of 25 - 50 MW was considered here.
In order for the produced hydrogen to be recognized as “green hydrogen”, it must, amongst other things, be based on “green electricity”. Wind power and photovoltaics are best suited regionally for this purpose. The potential for hydropower and biomass was assessed as too low and also too fragmented. For wind power, so-called priority areas for wind-energy utilization were designated in the Regionales Raumordnungsprogramm für den Großraum Braunschweig (Regional planning program for the Braunschweig metropolitan area) in 2008, in which further expansion can proceed (Regionalverband Großraum Braunschweig 2020). In addition, wind farms are already connected to the grid and feed in green electricity.

The power grid in the Salzgitter region is already at full capacity and it also supplies a number of large power consumers from industry. The integration of an additional load of 25 - 50 MW means an extensive expansion of the grid in order to be able to guarantee supply at all times. The extra-high voltage line planned for the new Volkswagen plant in Salzgitter and the power supply for electrolyzers of Salzgitter AG represent further new consumers.
In addition, enormous uncertainties exist from the legislative point in terms of the regulatory requirements to define hydrogen from renewable electricity as “green hydrogen”. At EU level, a broad and controversial discussion on this subject has been ongoing for several months. The corresponding criteria for the requirements of additionality and temporal and geographical correlation are set out in Article 27 of the Renewable Energies Directive in the so-called „RED II“ as a „Delegated Act“. The EU Commission has now published a final version of the delegated act on February 13, 2023, which contains adjustments to the draft of May 20, 2022. The legal acts still have to be adopted by the European Parliament and the Council (European Commission 2023).
A direct supply of electricity is made more difficult by the very fragmented ownership structures within the wind farms in the Salzgitter region. In addition, more attractive options are available in some cases for marketing wind power - even after the expiry of the EEG subsidy period: Competition already exists for green electricity, which consequently

Location conditions and possible scenarios:

Electrical energy

Water

Customers for the hydrogen

Optional customers for the by-products oxygen and waste heat

generally goes to “the highest bidder”. The expansion of wind power is not fast enough in this respect to be considered within the scope of this project.
The elaboration of a sufficient supply of electrical energy could therefore not be completed within the scope of the project.

Water

The limited availability of water had already become apparent even before the dry summer of 2022. An electrolysis plant with 25 MW of connected electric load requires around 6 m³ of water per hour at full load. For many regions in Germany, this is easily achievable, but must be taken into account at an early stage when selecting specific sites. Wastewater, for example, can also be made usable if it is suitable and specially purified; this, however, increases the investment requirement.

Customers for hydrogen/ synthetic methane

Particularly for new applications for hydrogen, e. g. in heavy-duty transport, there are many entry hurdles to overcome: The offtake is initially only very fragmented, and the associated logistics are expensive or do not yet exist, e. g. hydrogen refueling stations for busses or trucks; interest often only arises when there is greater availability and attractive prices. The chicken-and-egg problem is already familiar from the debate on the expansion of electromobility.
It therefore appears necessary to consider both the sides of the producers and customers as well as the infrastructure in an integrated way at the earliest possible stage.
The Salzgitter AG plant will require enormous quantities of hydrogen through to the 2030s, which cannot be rationally covered by exclusively local generation. The SALCOS project therefore considers not only local generation but also a connection to a hydrogen pipeline network.
Synthetic methane, in contrast, can benefit from an extensive, already existing infrastructure including connected consumers: the natural-gas network. As a result of the good gas quality, Synthetic methane can be mixed with natural gas in any desired concentration. Customers are therefore companies or private individuals who currently purchase natural gas. This is particularly relevant for applications that cannot be readily electrified, such as in coating technology or melting furnaces.

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Fig. 11: Evaluation of the different electricity purchase scenarios

Electricity supply	Advantages	Disadvantages
Via the power grid in the Salzgitter area	• High operating hours achievable (> 8000 h/a) • Very good utilization of investment	• Grid in Salzgitter urban area heavily utilized, 25–50 MW currently not available • Certification of “green H$_2$” is considered difficult • Grid fees must be paid in full
Via the power grid outside of the Salzgitter area	• Capacity may be more readily available at grid nodes, as there are fewer large consumers	• Hydrogen must be additionally transported to Salzgitter • Production plant not in the Salzgitter area
Direct supply from e. g. wind farm	• Renewable supply is clearly visible • Regulatory requirements easier to fulfill • Grid fees can be waived	• Only a small number of operating hours achievable via wind power directly, max. 2500 h/a • Ownership structure very fragmented • Production plant must be located in the immediate vicinity of the generation facility
Combination of grid supply and direct supply	• Identical to grid supply • Additional spatial restriction due to grid connection and e. g. wind farm	

11

Customers for by-products

During electrolysis, oxygen and heat are produced as by-products. Oxygen is utilized in a wide range of industrial processes, including metallurgy, the chemical industry and environmental technology. Oxygen is, however, a very readily available, low-cost gas, and utilization of the oxygen produced here only makes economic sense if it is located close to the consumers. One option could be the Salzgitter AG steelworks in Peine.

Waste heat from electrolysis unfortunately only occurs at low temperature levels of around 60 °C. The majority of the existing heat networks are operated at higher temperatures and therefore cannot use this waste heat. The utilization of a heat pump would, however, make this possible, and the plant could thereby provide a contribution towards a CO_2-free heat supply. In addition, the utilization in drying processes is of interest, provided that the spatial proximity is suitable.

Carbon dioxide (CO_2)

What is primarily described as harmful to the climate is actually a raw material for the production of synthetic gases, fuels and chemicals: CO_2.

The combination of hydrogen and CO_2 can produce, for example, synthetic methane, which can be added 1:1 to the existing natural-gas network as a “green” energy carrier. Alternatively, methanol, synthetic kerosene and even diesel can be produced in suitable plants - this wide variety is collectively known as power-to-liquid products. For a local power-to-x project, only synthetic methane was considered, for reasons of simplicity and availability of consumers.

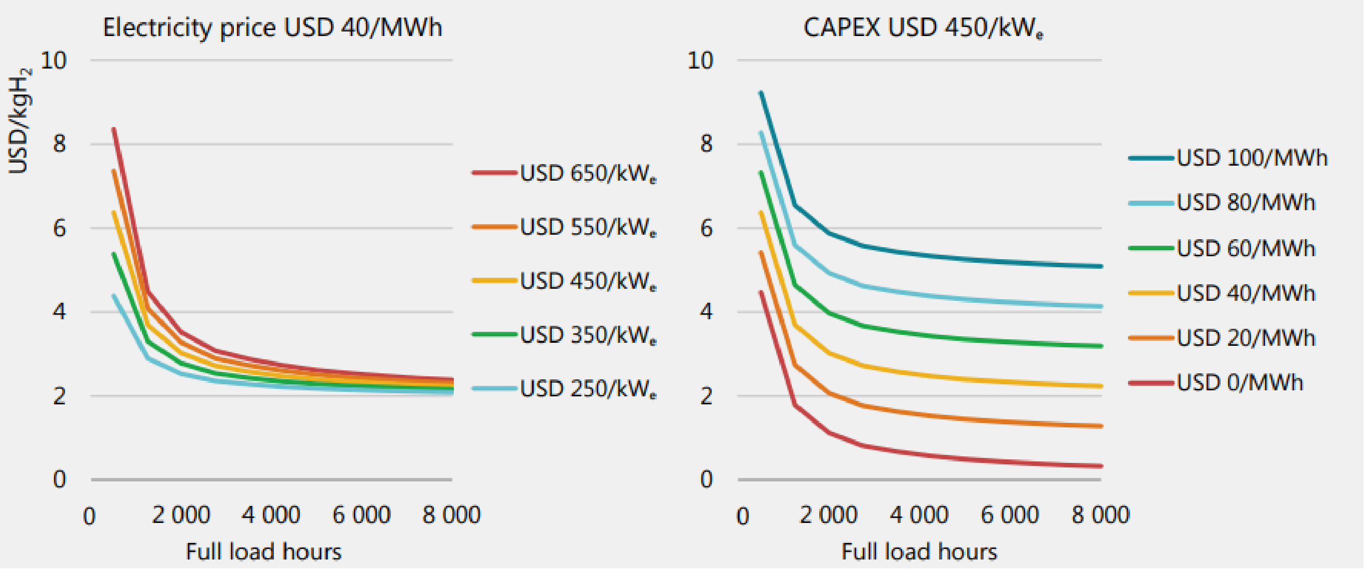
CO_2 is currently best available via so-called industrial point sources, e.g. in flue gases. The extraction of CO_2 from the atmosphere is currently still very expensive and only available on small scales. In the future, CO_2 can also be easily captured from Salzgitter AG’s direct-reduction plant for crude-steel production in the SALCOS project and then fed into a further utilization process. The region therefore has sufficient usable CO_2 available.

Here, too, however, there is a lack of clarity in the area of legislation: Similar to the definition of “green hydrogen”, discussions are still ongoing regarding the conditions that must be fulfilled for the use of CO_2 in CCU-projects producing a “green” carbon-based product from captured CO_2. CCU technologies would furthermore enable the CO_2 to be stored and used again when the synthetic methane is utilized by the end customer, as modeled in the closed-loop system for the methane import route (see chapter 2.2.7).

Conclusion regarding possible location

Within the scope of this project, it was not possible to conclusively address the power supply as a major location criterion. This is, however, the necessary prerequisite in order to be able to examine a selection of specific locations in more detail. In general, the Salzgitter region offers promising locations in terms of both producers and consumers. A more in-depth investigation of the power supply is proposed.

> **With a high number of full load hours per year, the cost of the electricity supply is dominant; with a lower utilization below 2,000 hours, the investment costs are dominant.**



12

Fig. 12: Influence of electrolysis investment costs and electricity prices in dependence of full utilization hours on hydrogen-production costs, taken from (IEA 2019)

3.4.2 Economic viability

The economic viability of power-to-X plants depends primarily on the following factors:

- Cost of electricity supply
- Operating hours per year
- Sales revenues from the products
- Investment costs
- Income from by-products

With a high number of full load hours per year, the cost of the electricity supply is dominant; with low full load hours below 2,000 hours, the investment costs are dominant (see **Fig. 12**). The goal of most projects is to achieve the highest possible utilization rate and, consequently, a high production volume; as a result, electricity costs are typically the decisive factor for economic viability. Conventional subsidy programs, which aim to cover a proportion of investment costs, therefore often fall short in the case of PtX plants, as the legal requirements do not allow support for ongoing operating costs. The H$_2$Global program (www.H2-global.de) addresses this point and closes the gap between the sales price and the currently still too high production costs by means of so-called "Contracts for Difference".
Transferred to the scenarios described above for electricity supply, this means that:

- Electricity supply via the grid allows high operating hours per year; the electricity price therefore becomes decisive here. Grid fees, taxes and charges are consequently also very relevant and often drive up the price of electricity, which calls profitability into question.
- Direct power supply from a wind farm allows only low operating hours, which makes the investment costs more important. Charges on the electricity price are lower here.

10 t

H_2 demand per day (estimate)

Regional H_2 rail network

For successful project development, it is necessary to find the broadest possible customer base for the sale of the hydrogen and the by-products.

Image source: ALSTOM

The investment costs for PtX plants are influenced by two mechanisms: "economy of scale" and "quantity effects". Electrolysis plants specifically become more economical the larger they are or the larger the utilized core modules (stacks) are (economy of scale). This is, however, part of the product development; at a certain point in time, therefore, only certain module sizes are available. In projects, investment costs can also be reduced via the plant size, i.e. the quantity of modules used (quantity effects). In this project, a size of 25 - 50 MW was selected in order to take advantage of both effects as far as possible.

Additional revenues from by-products have a positive effect on profitability, but can only compensate to a limited extent for excessively high electricity prices. Waste heat in particular can provide a relevant contribution as a CO_2-free heat supply if it is suitably remunerated. However, this requires a year-round heat supply, which is not feasible at all locations during the increasingly hot summers in Germany.

Oxygen is available industrially at very favorable prices and therefore has only a small impact on economic viability, as only small additional revenues can presumably be generated.

The present study demonstrates the high costs of transporting hydrogen; offtake should therefore be located in close proximity to production. Particularly in view of the high demand for hydrogen in German industry, this criterion is, however, hardly implementable.

From an economic point of view, the location selection should therefore set the following priorities:

- Low electricity prices, secured through long-term purchase agreement

- High number of operating hours per year
- Attractive purchase price, secured through long-term power purchase agreements
- Utilization of by-products

3.4.3 Hurdles facing a definite implementation

In the project, various locations in the Salzgitter region and, in some cases, beyond were identified and investigated with regard to their suitability for a hydrogen production plant. Logistical development and proximity to the power grid are given at a number of them, as is the spatial proximity to potential customers.

The greatest obstacle within the framework of this project development is presented by the power supply. The grid in the Salzgitter urban area is currently already heavily burdened and has to supply a number of large consumers (see also chapter 3.4.1). An alternative direct connection to e. g. a wind farm would require the bundling of a sufficient number of turbines; these are under highly fragmented ownership and have attractive sales options on the electricity market even after the expiry of the EEG subsidy period. The targeted capacity of 25 - 50 MW could therefore not be secured by the end of the project.

The planning was further complicated by regulatory uncertainty as to the conditions under which the produced hydrogen would be considered “green” according to RED II.

On the customer side, a certain degree of uncertainty can be observed as to when hydrogen will be required and to what extent, and what purchase price is acceptable. It hereby becomes clear that the chicken-and-egg-problem can ideally be solved holistically, i. e. by developing both the production and the utilization of hydrogen as well as the necessary logistics in the project in parallel. At least for the initial phase of the expected market ramp-up for hydrogen, this appears to be the most promising variant.

One approach to solving some of the described hurdles lies in the adaptation of the project consortium: An expansion to include project developers and providers of hydrogen logistics as well as companies that can introduce a bundling of “green electricity” into the project is proposed.

3.5 Regional H$_2$ customers using the example of hydrogen-powered local transport

For successful project development, it is necessary to find the broadest possible customer base for the sale of the hydrogen and the by-products. In this project, rail transport in the region around Salzgitter was identified as a potential customer for the green hydrogen. In a master’s thesis supervised by Alstom, various hydrogen requirements for individual rail networks in the Salzgitter metropolitan area were analyzed (Hinrichs 2021).

At approximately 0.80 million tonnes (as of 2020), greenhouse gas emissions from German rail transport are only slightly lower than those from national air transport and coastal and inland shipping (UBA 2022). Germany‘s state-owned rail network achieved an electrification level of 61 % in 2020, whereby 80 % of all rail traffic is carried on these electrified lines. Today, the remaining rail traffic is mainly realized through diesel multiple units or diesel locomotives. In Lower Saxony, around 1,600 of the total of approx. 3,000 route kilometers are electrified with overhead lines. In order to further reduce greenhouse gas emissions in rail transport, one focus is the further electrification of the rail network. The German government‘s goal is to electrify 70 % of the entire rail network by 2025. A second focus is on alternative propulsion technologies. These are primarily the battery overhead-line hybrid multiple units and hydrogen-fuel-cell hybrid multiple units. With these emission-free propulsion variants, the route traveled must be partially electrified or not electrified (Hinrichs 2021).

In a fuel-cell train, the electricity for propulsion is generated from hydrogen via a fuel cell. The hydrogen is refueled at special hydrogen filling stations and stored in pressurized tanks. The ALSTOM Coradia iLINT was presented in 2016 as the world’s first hydrogen train. The iLINT achieves a distance range of more than 1000 km. In 2022, the world’s first hydrogen-powered passenger service started in Bremervörde with a total of 14 hydrogen trains from Alstom and a filling station operated by Linde with 64 high-pressure tanks (500 bar) and a total capacity of 1,800 kg of hydrogen. As a result, 15 diesel trains were replaced (Alstom Group 2022), (Hinrichs 2021). For comparison, with a current PEM electrolysis of 1 MW capacity, 450 kg can be produced per day (H-TEC SYSTEMS 2022).

The possibility exists to replace routes in the Braunschweig metropolitan area that are currently operated with diesel multiple units with alternative propulsion technologies such as a hydrogen multiple unit. The Lower Saxony South-

1.

The production of green hydrogen in Germany is competitive.

Key messages to politics and industry:

east 1 and 2 diesel networks are particularly suitable for this. Hydrogen can be supplied to the trains by decentralized generation directly at the filling stations or by delivery from a larger production facility. Important boundary conditions for locations and the dimensioning of the filling stations include good accessibility for the trains, a maximum storage volume of 5 tonnes in order to avoid stricter requirements under the Störfallverordnung (hazardous incidents ordinance), and a certain level of redundancy in order to ensure the operation of the train fleet. As described in chapter 3.4.1, the location factors for the electrolyzers must also be considered, in particular the power supply. Ideal for the capacity utilization of the filling station would be a multimodal use, so that the filling station can supply different transport media such as trains, cars and trucks. The current legal situation, however, makes multimodal use of a hydrogen filling station difficult. Nevertheless, regulated train operation already ensures good utilization of such filling stations. For the above-mentioned networks in the Braunschweig metropolitan area, a projected demand of 7 to 10 tonnes of hydrogen per day has been estimated (Hinrichs 2021).
Texthervorhebung im pdf: "Up to 10 t H_2 demand per day (estimate) – Regional H_2 rail network – For successful project development, it is necessary to find the broadest possible customer base for the sale of the hydrogen and the by-products."

3.6 Key messages to politics and industry

The thesis paper "Kurzfristige Lösungen für grünen Wasserstoff in Salzgitter" (Short-term solutions for green hydrogen in Salzgitter) summarizes the fundamental findings of the project in 4 core messages which are explicitly addressed to politics and industry (Fraunhofer IST 2022):

1. The production of green hydrogen in Germany is competitive.
2. The German hydrogen market needs investment security quickly.
3. The acceleration of the market ramp-up can be achieved with existing technologies.
4. The supply to the industry requires an accelerated development of the hydrogen-pipeline network with connection to the German ports.

The project therefore aims to provide both orientation and thought-provoking impetus as to where action needs to be taken and what can be done to commence the development of a hydrogen market by 2030.

2.

The German hydrogen market needs investment security quickly

3.

The acceleration of the market ramp-up can be achieved with existing technologies.

4.

The supply to the industry requires an accelerated development of the hydrogen-pipeline network with connection to the German ports.

4. Outlook

One of the main findings of the project is the enormous complexity from hydrogen supply chains, in particular when considering near-term imports by ship from overseas with different hydrogen carriers. Short-term hydrogen supply chains based on GW scale electrolyzer plants face multiple uncertainties - and yet all the links in the supply chain must be dimensioned in detail based on multiple and intermittent renewable energy generation profiles in order to enable a cost-efficient functioning of the entire system.

In addition, interest in hydrogen has continued to grow strongly and has gained in overall quality. As a result, improvements in knowledge and market maturity of electrolysis, carrier synthesis and reconversion plants will occur in the future, thereby opening up further concrete perspectives for international hydrogen transport after 2030, including for liquid hydrogen and LOHC.

The GreenH$_2$SZ project has developed a variety of approaches that are suitable for subsequent work. Activities for a concrete implementation of a power-to-x plant in the Salzgitter region should be mentioned at this point.

Within the framework of the Wasserstoff Campus Salzgitter, the “Sector Coupling” project was launched back in 2020 with the aim of projecting a plant in the Salzgitter region for the production of green hydrogen and, if necessary, conversion into a PtX product, which is as close as possible to industrial symbiosis, so that the by-products – such as waste heat and oxygen – can also be utilized. The potential sites identified in the “GreenH$_2$SZ” project can be transferred to this project. In addition, it is proposed that the project consortium be suitably expanded and the points of power supply, logistics and offtake be specifically addressed. For the future, the Wasserstoff Campus Salzgitter will continue to offer a suitable project framework for this purpose. ■

Bibliography

Alstom Group (ed.) (2022): Weltpremiere: Erstes Netz mit 14 Wasserstoffzügen nimmt in Niedersachsen Betrieb mit Passagieren auf. Available online at: https://www.alstom.com/de/press-releases-news/2022/8/weltpremiere-erstes-netz-mit-14-wasserstoffzuegen-nimmt-niedersachsen.

Clean Hydrogen Partnership (ed.) (2022): Strategic Research and Innovation Agenda 2021 – 2027. Available online at: https://www.clean-hydrogen.europa.eu/about-us/key-documents/strategic-research-and-innovation-agenda_en.

Datta, Aparajita; Leon, Rafael de; Krishnamoorti, Ramanan (2020): Advancing carbon management through the global commoditization of CO_2: the case for dual-use LNG-CO_2 shipping. In: Carbon Management 11 (6), S. 611–630. DOI: 10.1080/17583004.2020.1840871.

Deutsche Energie-Agentur (ed.) (2021): dena-Leitstudie Aufbruch Klimaneutralität. Available online at: https://www.dena.de/newsroom/meldungen/dena-leitstudie-aufbruch-klimaneutralitaet/.
Deutsche Energie-Agentur (ed.) (2022): Analyse ENERGY HUB Port of Wilhelmshaven. Available online at: https://www.dena.de/newsroom/publikationsdetailansicht/pub/analyse-energy-hub-port-of-wilhelmshaven/.

EHB (ed.) (2022): European Hydrogen Backbone. A EUROPEAN HYDROGEN INFRASTRUCTURE VISION COVERING 28 COUNTRIES. Available online at: https://ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf.

Element Energy (ed.) (2018): Shipping CO_2 - UK Cost Estimation Study. Available online at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/761762/BEIS_Shipping_CO2.pdf.

European Commission (Hg.) (2022): REPowerEU Plan. COM(2022) 230 final. Online verfügbar unter https://eur-lex.europa.eu/resource.html?uri=cellar:fc930f14-d7ae-11ec-a95f-01aa75ed71a1.0001.02/DOC_1&format=PDF.

European Commission (Hg.) (2023): Commission sets out rules for renewable hydrogen. Online verfügbar unter https://ec.europa.eu/commission/presscorner/detail/en/ip_23_594.

Fraunhofer IST (2022): Kurzfristige Lösungen für grünen Wasserstoff in Salzgitter - Thesenpapier GreenH$_2$SZ. Published by the Fraunhofer Institute for Surface Engineering and Thin Films IST. Available online at: https://wasserstoff-campus-salzgitter.de/.

Hinrichs, K. (2021): Masterarbeit „Vom Diesel zum Wasserstoff - Umstellung des Schienennahverkehrs am Beispiel Salzgitter". Unter Mitarbeit von R. Hofstädter (Alstom Group). TU Braunschweig.

H-TEC SYSTEMS (ed.) (2022): H-TEC PEM-Elektrolyseur ME450. Available online at: https://www.h-tec.com/produkte/detail/h-tec-pem-elektrolyseur-me450/me450/.

IEA (ed.) (2019): The Future of Hydrogen. Paris. Available online at: https://www.iea.org/reports/the-future-of-hydrogen.

IGU (2022): World LNG Report 2022. Published by International Gas Union. Available online at: https://www.igu.org/resources/world-lng-report-2022/.

Institut für Seeverkehrswirtschaft und Logistik (ISL) (ed.) (2021): Die Rolle der maritimen Wirtschaft bei der Etablierung einer deutschen Wasserstoffwirtschaft. Available online at: https://dmz-maritim.de/studie-wasserstoff_2021/.

IRENA (2022a): Global hydrogen trade to meet the 1.5°C climate goal: Part II - Technology review of hydrogen carriers. Published by International Renewable Energy Agency. Abu Dhabi. Available online at: www.irena.org/publications.

IRENA (2022b): Global hydrogen trade to meet the 1.5°C climate goal: Part III - Green hydrogen cost and potential. Published by International Renewable Energy Agency. Abu Dhabi. Available online at: www.irena.org/publications.

IRENA (2022c): Renewable technology innovation indicators: Mapping progress in costs, patents and standards. Published by International Renewable Energy Agency. Abu Dhabi. Available online at: www.irena.org/publications.

Kawasaki (2021): A seamless hydrogen supply chain. Published by Springer Nature. Available online at: https://www.nature.com/articles/d42473-020-00544-8.

Kost, C.; Shammugam, S.; Fluri, V.; Peper, D.; Memar, A.; Schlegl, T. (2021): Stromgestehungskosten Erneuerbare Energien. Published by the Fraunhofer Institute for Solar Energy Systems ISE. Available online at: https://www.ise.fraunhofer.de/de/veroeffentlichungen/studien/studie-stromgestehungskosten-erneuerbare-energien.html.

Marine insight (ed.) (2022): 5 Biggest Tanker Ships In the World. Available online at: https://www.marineinsight.com/marine/5-biggest-tanker-ships-in-the-world/.

Northern Lights (ed.) (2022): First steel cut for Northern Lights CO$_2$ transport ships. Available online at: https://norlights.com/news/first-steel-cut-for-northern-lights-CO2-transport-ships/.

Offshore Energy (ed.) (2022): South Korea's first methanol-powered tanker named. Available online at: https://www.offshore-energy.biz/south-koreas-first-methanol-powered-tanker-named/.

Open Grid Europe (ed.) (2022): CO$_2$-Netz. Online verfügbar unter https://www.CO2-netz.de/.

Regionalverband Großraum Braunschweig (ed.) (2020): Änderung des Regionalen Raumordnungsprogramms 2008 für den Großraum Braunschweig. „Weiterentwicklung der Windenergienutzung“. Available online at: http://www.regionalverband-braunschweig.de/wind/.

Roussanaly, Simon; Deng, Han; Skaugen, Geir; Gundersen, Truls (2021): At what Pressure Shall CO$_2$ Be Transported by Ship? An in-Depth Cost Comparison of 7 and 15 Barg Shipping. In: Energies 14 (18), S. 5635. DOI: 10.3390/en14185635.

Sadler, Dan; Anderson, Henrik Solgaard; Sperrink, Martin; Cargill, Al; Sjøvoll, Merethe; Åsen, Knut Ingvar et al. (2018): H21 North of England. H21 NoE Report/2018. Available online at: https://H21.green/projects/H21-north-of-england/.

UBA (2022): Nationale Trendtabellen in der Abgrenzung der Sektoren des Klimaschutzgesetzes (KSG). Published by the Umweltbundesamt. Available online at: https://www.umweltbundesamt.de/themen/klima-energie/treibhausgas-emissionen.

Imprint

Publisher:
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Publication:
05/2023

The results were achieved as part of the funded project “Conceptualization of a feasible green hydrogen supply for the Salzgitter region within the context of the European hydrogen strategy” (GreenH$_2$SZ). Funding was financed from funds of the grants for special structural aid measures of the State of Lower Saxony to the City of Salzgitter (Salzgitterhilfe).

Citation:
Fraunhofer-Institute for Surface Engineering and Thin Films IST (ed.) (Fraunhofer IST, 2023) “Conceptualization of a feasible green hydrogen supply for the Salzgitter region within the context of the European hydrogen strategy”

Wasserstoff Campus
Salzgitter

Image source: Salzgitter AG

Project partners:

- ALSTOM
- Amt für regionale Landesentwicklung Braunschweig
- avacon
- BOSCH Technik fürs Leben
- Fraunhofer IST
- MAN Energy Solutions
- Salzgitter
- SALZGITTER AG Mensch, Stahl und Technologie
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