cruh21
enabling energy innovation

Masterplan Hydrogen City of Cuxhaven

Final Report | January 2023

Client

Agentur für Wirtschaftsförderung Cuxhaven
Kapitän-Alexander-Straße 1
27472 Cuxhaven

Author

cruh2**1** GmbH
Erste Brunnenstraße 1
22459 Hamburg

Dr. Stefan Wahlefeld, Senior Consultant
Tel.: +49 40 3346553-63
wahlefeld@cruh21.com
Dr. Christine Partmann, Meryem Maghrebi, Hanna Naoumis, Sven Stephan

Table of contents

1 Hydrogen and its derivatives - significance for the energy transition

In a future energy system that is based on renewable energies and, in accordance with the commitments of the Paris Climate Agreement, the European Green Deal and, in Germany, the Climate Protection Act, must be completely greenhouse gas neutral throughout Europe by 2050 and throughout Germany by 2045, hydrogen based on renewable energies will play a key role.

As an important link, hydrogen enables the demand-oriented use of volatile (fluctuating) renewable wind and solar energy. By converting and storing the irregularly generated electricity in the form of hydrogen, it can be used as needed in material or energetic form (electricity/heat) downstream. In this way, the use of green hydrogen and its derivatives can also decarbonise those sectors in the future that are currently still dependent on fossil fuels and cannot be directly electrified. These include, above all, the steel and chemical industries as well as parts of the transport and heating sectors. Here, hydrogen has a justification and is the necessary means to an end. It is important to note that it is not a matter of using hydrogen per se as a generally valid substitute for fossil fuels, but precisely where fossil fuels cannot be replaced by direct use of electricity or where the hydrogen molecule serves as a basic material.

Against this background, the topic of hydrogen has gained massive importance in recent years. The world's major economies are currently discussing possible options for action, preparing corresponding measures and adopting targeted hydrogen strategies. Japan was the first country in the world to present a national hydrogen strategy at the end of 2017. More than 33 other countries followed suit and published a hydrogen strategy by September 2022. In July 2020, the European Union presented its own hydrogen strategy for a climate-neutral Europe. More than half of these strategies have concrete targets for expanding electrolyser capacities. These are to add up to 88 gigawatts by 2030. (Bloomberg NEF 2022)

The countries are focusing on reducing greenhouse gas emissions, diversifying their energy sources and improving security of supply. Many governments, such as those of South Korea, Germany, the Netherlands and Australia, also expect economic benefits from the use of the alternative energy carrier through the development of a national hydrogen economy, the creation of jobs or hydrogen and technology exports. In order to promote the ramp-up, the majority of countries are focusing on different types of hydrogen production in the short to medium term, including the use of fossil-derived grey hydrogen (e.g., with the help of conventional natural gas), as well as blue hydrogen, which is fossil-derived with CO_2 capture and storage (CCS). In the long term, however, the focus of most hydrogen strategies, especially in the EU, is on the use of green hydrogen based on renewable energies. (Albrecht et al. 2020)

1.1 Properties of hydrogen

Hydrogen - the most common element in our universe - is present in bound form in almost all organic compounds. It is the first element in the periodic table and consists of one proton and one electron. This makes it the smallest and lightest element in terms of atomic weight: 14 times lighter than air. In molecular form (H_2), two hydrogen atoms combine. Under normal conditions, hydrogen is a colourless, odourless, and tasteless gas and has a density of 0.0841 kg/m^3. Liquefaction only occurs at very low temperatures (-252.8°C) at normal pressure of 1.013 bar.

Hydrogen has the following positive properties:

+ Hydrogen is neither toxic nor corrosive or radioactive, nor does it self-ignite.
+ Hydrogen burns with a colourless flame without residues, i.e. only water vapour is produced during its combustion and a small amount of nitrogen oxide through the reaction with atmospheric nitrogen.
+ Compared to all other energy carriers, hydrogen has the highest energy density per kilogram (gravimetric density): Hydrogen: 33.3 kWh/kg, natural gas: 13.9 kWh/kg, heating oil: 11.4 kWh/kg

The gravimetric energy density is of great practical interest because the higher the energy density, the lighter this energy carrier is for the same amount of stored energy compared to another energy carrier with a smaller energy density. However, this is contrasted by the comparatively particularly low energy density per volume (volumetric energy density) of hydrogen at ambient pressure. This can be increased by compression (pressure increase) or liquefaction (cooling). At today's usual operating ranges, the volumetric energy density of liquid hydrogen between 2 and 4 bar is twice as high at up to 2.3 kWh/l compared to compressed gaseous hydrogen (cGH_2) at 700 bar at 1.3 kWh/l. Significantly higher volumetric energy densities are achieved with diesel. Figure 1 illustrates the volumetric and energetic energy content of compressed hydrogen (cGH_2) at 350 bar and 700 bar, liquid hydrogen (LH_2), ammonia (NH_3) as a hydrogen carrier and diesel.

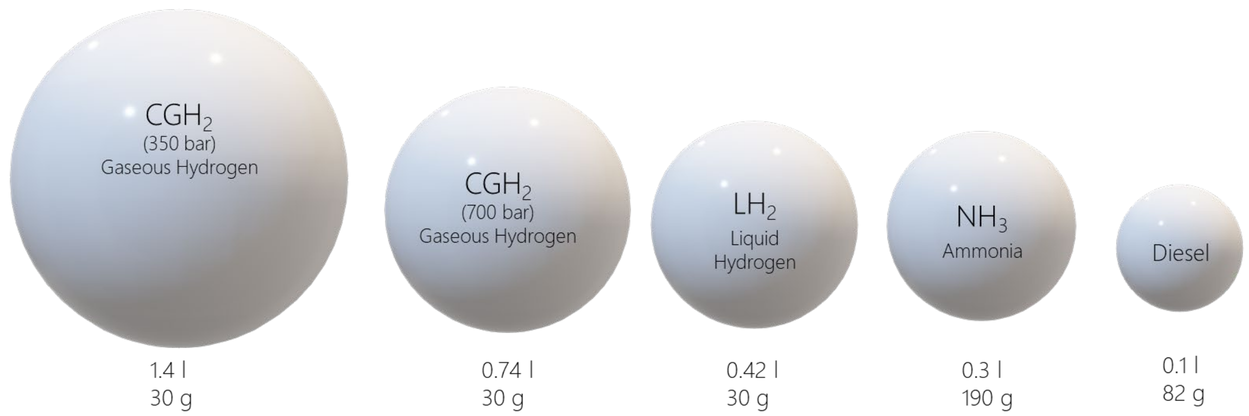

Figure 1: Volumetric and gravimetric energy density of fuels (drop sizes with fixed energy content of 1 kWh)

When handling hydrogen, the high rate of ignition in contact with air must be considered. Therefore, appropriate measures such as the ventilation of closed rooms and the permeability of the containers must be taken into account. (Manfred Klell et al. 2018)

1.2 Hydrogen production and hydrogen colour theory

Colours of hydrogen

Natural hydrogen, so-called white hydrogen, only occurs in very small concentrations worldwide and is therefore not considered in detail in this report. Most of the hydrogen on Earth is in chemically bound form, so it has to be extracted from chemical compounds by means of energy. The processes by which this production occurs are identified by colours and differ in whether the corresponding production pathway is based on fossil or renewable energies, whether greenhouse gases are produced and how these are handled.

Pink hydrogen: Production by water electrolysis using nuclear power

Yellow hydrogen: Production by water electrolysis using an electricity mix

Green hydrogen: Production by water electrolysis, thermolysis or photolysis using renewable electricity, with no CO_2 emissions during the production process. Alternatively, green hydrogen can be produced by gasification or reforming of biomass.

Turquoise hydrogen: Can be obtained by pyrolysis. This process produces solid carbon.

Blue hydrogen: Production from fossil fuels, usually applying steam reforming of natural gas. This process produces CO_2, which is captured and stored, so-called Carbon Capture and Storage (CCS).

Grey hydrogen: Production from fossil fuels, usually using steam reforming of natural gas. This process produces CO_2, which is not captured and stored compared to turquoise hydrogen.

Black hydrogen: Produced by gasifying coal, so it is a very polluting process that produces CO_2 and carbon monoxide as by-products.

The Figure 2 provides a detailed overview of the aforementioned processes for the production of hydrogen with information on the feedstocks and energy sources, the by-products of the process and the resulting colour coding of the hydrogen.

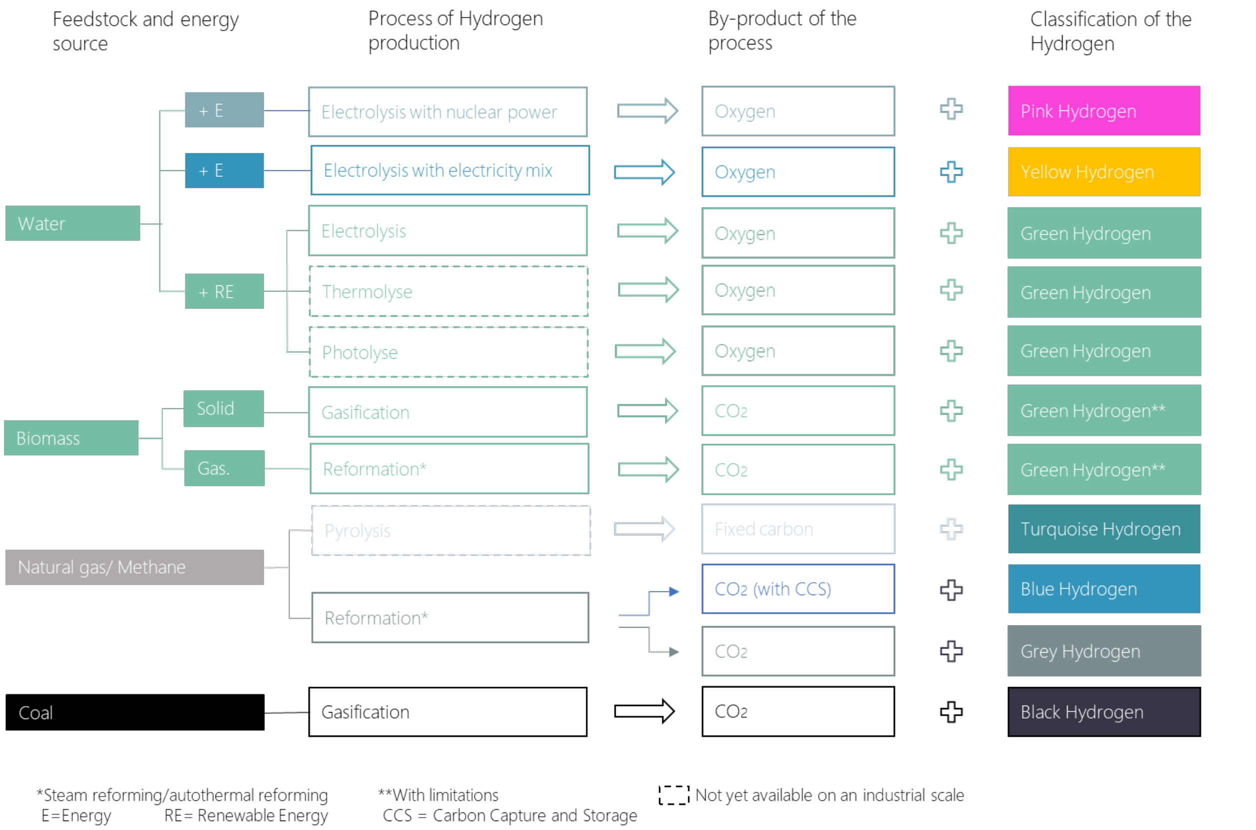

Figure 2: Production of hydrogen and colour coding (German Advisory Council on the Environment 2021)

Production of green hydrogen by water electrolysis

The production of hydrogen from water and electricity is called water electrolysis or electrolysis. If electricity from renewable energy sources is employed, it is called green hydrogen. In an electrical-chemical reaction, water is broken down into hydrogen and oxygen. The electric current can thus be stored in the form of a chemical molecule (here: hydrogen). The device which executes this material conversion is called an electrolyser. There are different electrolysers, which differ mainly in the applied electrolyte, the operating temperature and the design of the electrolysis cell. The four best-known types of electrolysis - the AEL, the PEM, the AEM and the SOEC electrolysis - are described below and their mode of operation is briefly explained. Table 1 summarises the key figures for electrolyser technologies in 2020 and 2050:

- **AEL - Alkaline electrolysis:** In alkaline electrolysis (abbreviated to AEL), a potassium hydroxide solution is applied as the electrolyte. The two electrodes are separated by a permeable membrane, the so-called diaphragm. These are immersed in an aqueous alkaline solution. When a voltage is applied, oxygen is produced at the anode and hydrogen at the cathode. (Manfred Klell et al. 2018)

  AEL has been used industrially since the end of the century before last and already showed good efficiencies in the 20th century as well as long running times in stationary continuous operation. (Fraunhofer 2019)

- **PEM - Proton Exchange Membrane Electrolysis**: In proton exchange membrane electrolysis (PEM), or polymer electrolyte membrane electrolysis, a thin membrane made of a thermoplastic (ionomer) is applied as the electrolyte. A gas-tight membrane separates the electrodes so that only positive hydrogen ions can pass through. Precious metals are employed to prevent corrosion. The process requires a high degree of water purity. (Manfred Klell et al. 2018)

  PEM electrolysis has been successfully utilized in niche applications for about two decades. In view of its compact design, suitability for operation under pressure and high dynamics during rapid load changes, this technology is considered well suited for coupling with renewable energies. (Fraunhofer 2019)

- **AEM - Anion Exchange Membrane:** The AEM cell is constructed in the same way as the PEM cell; it can also be operated under pressure and with high electrical power. Here, too, an ion-conducting polymer membrane is applied. The electrodes are coated with catalyst particles. In contrast to PEM electrolysis, non-precious metals such as nickel can be used, as the process operates in an alkaline environment. As with the AEL process, water splitting appears on the cathode side. (Hickner et al. 2013)

- **SOEC - Solid Oxide Electrolysis Cell:** In solid oxide electrolysis (SOE), a solid porous ceramic material separates the two half cells. Steam is introduced into the porous cathode. When current flows, the vapour moves to the cathode-electrolyte interface and forms pure H_2 and oxygen ions. The hydrogen collects at the cathode surface while the oxygen ions move through the dense electrolyte. This must be so dense that vapour and hydrogen gas cannot diffuse through and prevent the recombination or oxyhydrogen reaction of H_2 and O_2. The oxygen ions are oxidised at the interface between electrolyte and anode to pure oxygen gas, which collects on the surface of the anode. (Manfred Klell et al. 2018)

  This type of electrolysis is currently in transition from research to industrial application and is particularly well suited for coupling with industrial processes, as it has very good electrical efficiency when waste heat is available on site at a temperature level of 200 °C or higher. (Fraunhofer 2019)

There are about 40 manufacturers of water electrolysers (see Table 11; in the appendix), with more than half being European companies, these differed in terms of applied technology, hydrogen quantity and power class. According to a NOW study, the current market shares for electrolysers are 80% AEL, 18% PEM and 2% SOEC. (Now GmbH 2018a) Regarding the timing of the study, AEM technology was not considered.

Differences in cost and performance are expected to narrow over time as innovation and mass deployment of the various electrolysis technologies contribute to cost convergence. (IRENA 2021) In Section 1.6 the impact of decreasing investment costs on the cost of green hydrogen is discussed in more detail.

Table 1: Key figures for electrolyser technologies in 2020 and 2050 (IRENA 2021)

	2020				2050			
	AEL	**PEM**	**AEM**	**SOEC**	**AEL**	**PEM**	**AEM**	**SOEC**
Temperature in °C	70 - 90	50 - 80	40 - 60	700 - 850	> 90	80	80	< 600
Pressure in bar	< 30	< 70	< 35	< 10	> 70	> 70	> 70	> 70
Efficiency in kWh/kg_{H2}	50-78	50-83	57-69	45-55	< 45	< 45	< 45	< 40
Service life in h	60.000	50.000-80.000	>5.000	<20.000	100.000	100.000	100.000	80.000
System costs in EUR/kW	440 - 875	610 - 1.200	-	-	< 175	< 175	< 175	< 260

1.3 Storage methods for hydrogen

Since hydrogen is not always employed directly at the place of production or immediately after production, technologies for storage and transport are required. From a technical point of view, there are various possibilities for hydrogen storage (see Figure 3). In the following, the currently most relevant technologies (marked in red) are examined in more detail.

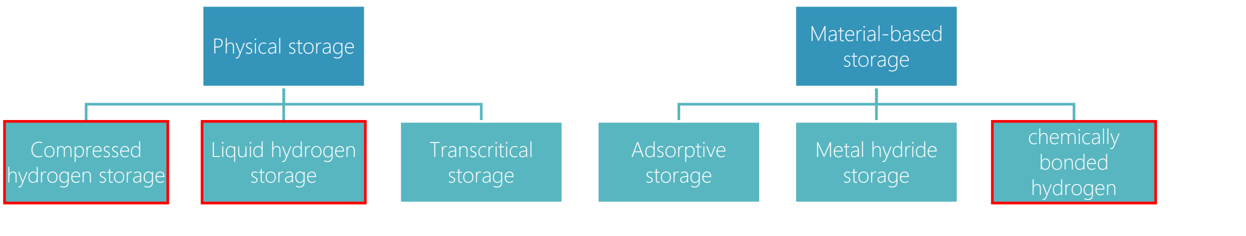

Figure 3: Storage methods for hydrogen

a) Pressurised hydrogen storage

The most important commercial storage method - especially for end users - is the storage of hydrogen as a compressed gas. In pressurised storage, the hydrogen is compressed and stored in pressurised tanks. Today, hydrogen is transported almost exclusively by road in pressure tanks, mostly in the pressure stages 200 bar or 300 bar. In terms of pressure tanks, a distinction is made between steel and fibre composite tanks, type I to type IV, which can be designed for pressures between 10 bar and 1000 bar.

Such high-pressure storage tanks are particularly suitable for small storage quantities and are therefore often operated by the end user in vehicles such as trucks or cars. The higher the pressure, the greater the achieved storage density. For commercial vehicles, for example, a pressure level of 350 bar and 700 bar for passenger cars have become established. At 350 bar the density is approx. 24 kg/m^3 at 700 bar approx. 40 kg/m^3. The energy required for compression to 700 bar is approx. 12 % of the energy content of the hydrogen.

In addition, large quantities of hydrogen can putatively be stored in underground caverns in the future. There, the hydrogen can be stored under pressure. In the USA, Linde operates the world's first storage cavern for high-purity hydrogen. In Germany, the energy supplier EWE is researching an underground cavern storage facility in salt rock together with the German Aerospace Centre, Institute for Networked Energy Systems. (DVGW 2022; Warnecke and Röhling 2021; Meinen 2022)

b) Liquid hydrogen storage

Liquefying hydrogen (LH_2) is another option for storage and transport, enabling significantly more hydrogen to be transported and stored with the same storage volume. For liquefaction, the hydrogen is cooled to -253 °C (boiling point of hydrogen at ambient pressure (1.013 bar) -252.8°C), compressed (<10 bar) and stored in so-called cryotanks. The storage density is then 71 kg/m³. LPG storage tanks are cheaper for larger hydrogen storage quantities and are therefore often applied for transport over long distances. The disadvantage is the evaporation of the hydrogen, which is caused by heating. The energy input for liquefied gas storage can be divided into the following proportions, each related to the stored energy content: (Peter Kurzweil and Otto K. Dietlmeier 2018)

- 28-46 % for liquefaction depending on quantity and operational method
- 6 % for transport between liquefaction station and filling station (diesel and petrol 0.2 %)
- up to 3 % per day due to boil-off losses
- Evaporation losses during decanting.

Compared to compressed gas storage, the pressure does not pose a problem for the design of the tank. With liquefied gas storage, on the other hand, great effort must be made in the thermal insulation of the tank and the pipes. Despite good thermal insulation of the tank, a heat flow from the environment cannot be avoided. This leads to partial evaporation of the hydrogen. Furthermore, there is a greater demand for temperature-controlled transport, which places additional technical demands on the logistics.

c) Chemically bound hydrogen

When hydrogen is stored in a chemical bond, it is converted by a chemical reaction into another substance that can be accumulated and transported, for example, without pressure at room temperature.

LOHC technology (Liquid Organic Hydrogen Carrier) utilizes an liquid organic carrier to store and transport hydrogen at ambient temperatures. LOHC has a particularly high energy density and applies a carrier material which is difficult to ignite. This enables hydrogen to be stored and transported easily, like petroleum or fuels. To produce LOHC, hydrogen is chemically bonded to the liquid carrier (hydrogenation). This reaction is exothermic and about 10 kWh of thermal energy is released, thus, increasing the efficiency of the process if the resulting waste heat can be capitalized. In order to be able to dissolve hydrogen from the LOHC (dehydrogenation), energy must be supplied in the form of heat (endothermic reaction). This requires about 11 kWh of thermal energy per kilogram of hydrogen produced. This can be generated by the dissolved hydrogen itself, e.g., by combustion.

Other possibilities are, for example, the storage of hydrogen in the form of ammonia or methanol. Both are very common chemicals that are further processed as a basic material into various products. Methanol, for example, is one of the most widely produced organic chemicals and a starting material for a variety of chemical processes, and ammonia is necessary, for example, in the production of fertilisers. Accordingly, there are already existing infrastructures and experience with the transport and storage of both chemicals. Furthermore, both can also serve as energy carriers and are referred to as synthetic fuels or e-fuels. When burnt, these emit only water and nitrogen. The shipping industry, for example, relies on methanol as a fuel for its large cargo ships. Liquid ammonia has the advantage of having a higher energy density than pure hydrogen: one cubic metre of ammonia contains 50% more energy (see Figure 1). Moreover, ammonia becomes liquid already at -33 °C, whereas pure hydrogen only at -253 °C. This means that the effort required to transport hydrogen in the form of ammonia is significantly less than for pure hydrogen. If the hydrogen bound in the ammonia is required (and not the chemical as such), the chemical can be split into nitrogen and hydrogen in an endothermic ammonia cracking process. This process is very energy-intensive and is currently being researched, for example, in the BMBF-funded hydrogen lead project TransHyDE-Campfire.

1.4 Means of hydrogen transport

Cost comparison studies show that there is no universal solution for hydrogen transport that is equally suitable for all situations examined. The form of end use of the hydrogen and the distance between producer and consumer emerged as the decisive factors in the choice of a transport solution. (Frithjof Staiß et al. 2022) Different transport possibilities are described in the following, whereby mainly the transport of pure hydrogen is discussed and not the transport of hydrogen in a chemically bound form.

a) Road transport

A main transport route for hydrogen is currently the road. The hydrogen is transported by tractor units with semi-trailers (see Figure 4), in which the hydrogen is stored. The transportable hydrogen capacity is limited by the permissible total weight of a truck. In Germany, the permissible total weight for the largest commercial vehicle class is 44 t, whereby after deduction of the tractor's own weight, approx. 28.5 t remain for the trailer including loading. Depending on the trailer design, pressurised hydrogen, liquid hydrogen or LOHC can be transported.

- The transport capacity of pressurised hydrogen by trailer depends on the respective pressure of the containers, so that, for example, 300 kg hydrogen/trailer can be transported at 200 bar (container type I), 800 kg/trailer at 300 bar and 1100 kg/trailer at 500 bar (container type IV).
- Liquid hydrogen is transported in LH_2 trailers, which can carry up to 4,300 kg due to the higher density of liquid hydrogen.
- For the transport of LOHC, conventional trailers used for the transport of diesel or petrol can be used. In this case, approx. 1,620 kg of hydrogen can be effectively transported.[1]

In addition to the cross-modal regulations, the regulations for the carriage of dangerous goods by road are relevant (BMDV 2022b, 2022a)

Figure 4: Hydrogen transport by road ©malp/stock.adobe.com

b) Rail transport

There is currently no hydrogen transport by rail in Germany. According to a feasibility study by Deutsche Bahn commissioned by the State Energy Agency of Hesse, this is an alternative with the potential to compete with road transport. Hydrogen transport containers can be transported by rail in standard 40-foot ISO containers, which can also be transported by road tractors as trailers. Since these standard containers are already applied in everyday freight transport, the logistics infrastructure is already in place. At present, however, the standard containers

[1] With a maximum payload of 28.5 t and 6.2 % mass of stored hydrogen, the amount of hydrogen is 1,800 kg, whereby only 90 % of the stored hydrogen can be dehydrated.

have not been approved or certified as MEGC (Multiple-Element Gas Container) versions for rail transport in order to be able to transport hydrogen by rail. Containers manufactured by the company NPROXX have a usable filling volume of compressed hydrogen in the 300 bar and 500 bar versions of 700 kg and 1000 kg, respectively. For the transport of LOHC, it might even be possible to use mineral oil tank wagons which are already in daily application. For train transport, a maximum train length of 700 m and a maximum permissible wheel load of 22.5 t must also be observed. The specific transport costs are a very volatile cost factor in rail transport, which depends to a large extent on the individual route parameters such as route utilisation, shunting stops and local framework conditions on the transport route. A valid statement as to whether delivery by rail is competitive in the future must be calculated for each individual case. (Vito Milella et al. 2020)

c) Ship transport

In view of the high demand from 2030 onwards, it can be assumed that significant shares of hydrogen and its derivates will be imported to Germany in the future (see Figure 5). (Zentralverband der deutschen Seehafenbetriebe e. V. 2021) On a global level, shipping could therefore play an important role as an additional transport medium for the development of a hydrogen distribution infrastructure. In their study, Staiß et al. analyse options for importing green hydrogen to Germany by 2030. (Staiß et al. 2022) The focus here is particularly on the transport by ship of LH_2, LOHC, ammonia, methanol and synthetic Fischer-Tropsch products. The transport of gaseous hydrogen is not considered economical due to the low energy storage density.

The dangerous goods properties of gaseous hydrogen are declared as "extremely flammable" according to the internationally valid GHS labelling, which is why transport containers such as tank containers must be placed in special locations on ships and must be labelled with warning signs for hazard number 23 and UN number 1049. The transport of hydrogen on ships is regulated by the International Maritime Dangerous Goods (IMDG) Code together with the requirements of the International Convention for the Safety of Life at Sea (SOLAS). (Zentralverband der deutschen Seehafenbetriebe e. V. 2021)

On a national level, river connections could play a crucial role, although literature regarding hydrogen transport by ship on a national level is not yet available.

Figure 5: Ship transport of liquid hydrogen with composite cryotanks ©AA+W/stock.adobe.com

d) Pipeline transport

For the transport of gaseous energy carriers, the re-use of existing or former gas pipelines is heavily discussed. Hydrogen can be mixed into existing natural gas pipelines and then employed to provide heat in conventional natural gas boilers in households, commerce and industry. The existing DVGW regulations already allow admixtures of just under 10% by volume into the existing gas network wherever there are no restrictions due to specific applications. Technical surveys by the German Technical and Scientific Association for Gas and Water (DVGW), among others, assume that up to 20 vol.- % hydrogen could be added to the natural gas supply. The admixture reduces the value of the hydrogen and causes differences in the quality of the transported natural gas in Europe. Consumers along the pipeline who cannot handle the admixed hydrogen must be protected; customers with specific hydrogen applications must first separate the admixed hydrogen from the natural gas stream again before feeding it into their processes. To this end, Linde has built the world's first demonstration plant for the recovery of hydrogen from natural gas streams on an industrial scale in Dormagen. HISELECT Evonik membrane technology is used in Dormagen. The processed gas mixture contains between 5 and 60 % hydrogen. The hydrogen separated by the membrane has a concentration of up to 90 %. If a customer requires a higher concentration for his applications, a pressure swing adsorption (PSA) system is additionally applied. This enables a degree of purity of up to 99.9999 %. (DVGW 2022)

For selected locations, there are also local/regional hydrogen pipeline networks whose utilization could gain in importance in the future. So far, there are only three pure hydrogen pipelines in Germany: in the Ruhr area, in Leuna (Saxony-Anhalt) and Höchst near Frankfurt. The operators of the natural gas networks are planning to expand their hydrogen networks to a length of 500 km by 2025.

In view of REPowerEU and in response to the accelerated development of the hydrogen market, a vision for a European Hydrogen Backbone (EHB) was developed in April 2022, Figure 6) and presented. According to this vision, five pan-European hydrogen supply and import corridors could be created by 2030, connecting industrial clusters, ports and hydrogen valleys with hydrogen supply regions. The hydrogen infrastructure can subsequently be developed into a pan-European network of almost 53,000 km by 2040, largely based on the reused existing natural gas infrastructure. In addition, the maps show possible routes that could emerge, including potential offshore interconnectors and pipelines in regions outside the area where EHB members are active. The onshore backbone would amount to over 1,000 km. (van Rossum et al. 2022) Table 2 summarises the advantages and disadvantages of each transport mode.

Figure 6: Hydrogen transport by pipeline ©malp/stock.adobe.com

Table 2: Advantages and disadvantages of the means of transport

Transport per	Advantages	Disadvantages
street	▪ flexible transport to the consumer if no pipeline is available ▪ use of different storage systems, pressure vessels for gaseous hydrogen and tanks for liquid hydrogen ▪ already proven technology	▪ relatively high transport costs ▪ transport only possible in small quantities ▪ sustainable transport only possible with e-trucks or hydrogen-powered trucks
rail	▪ transport of larger quantities than possible by road ▪ environmentally friendly transport with electrified route network or employment of fuel cell trains ▪ relieving the road network	▪ no approved transport containers so far ▪ transport currently still more expensive compared to road transport
ship	▪ suitable transport option for longer distances, for example between continents ▪ transport in liquid form reduces effort and uses higher energy density ▪ sustainable transport for ships with hydrogen as propulsion energy	▪ if applicable, conversion losses of the hydrogen ▪ energy input for transport ▪ greenhouse gas emissions from cargo ships with diesel engines ▪ very long transport time (depending on the route)
pipeline	▪ transport of large quantities ▪ pipelines can supply many consumers with hydrogen ▪ use of former natural gas pipelines possible ▪ gaseous transport possible ▪ cheapest transport within Germany and Europe ▪ low losses and low transport costs ▪ low running costs	▪ producers and consumers must be connected to the pipeline network ▪ only a small network of pipelines available so far ▪ high capital expenditure for the expansion of the transport pipelines ▪ long planning and approval procedures and construction times for new pipelines ▪ high expenditure for connection to the mains ▪ greater expenditure of electrical energy (compressor power) to maintain the transport pressure (greater pressure loss with the same energy content)

1.5 Areas of application for hydrogen

The application range of hydrogen extends across all sectors (industrial sector, transport sector, building sector and power sector) (see Figure 7), with current hydrogen usage dominated by industrial applications. If green hydrogen is applied, this contributes to the defossilisation and greenhouse gas reduction of energy-intensive industries.

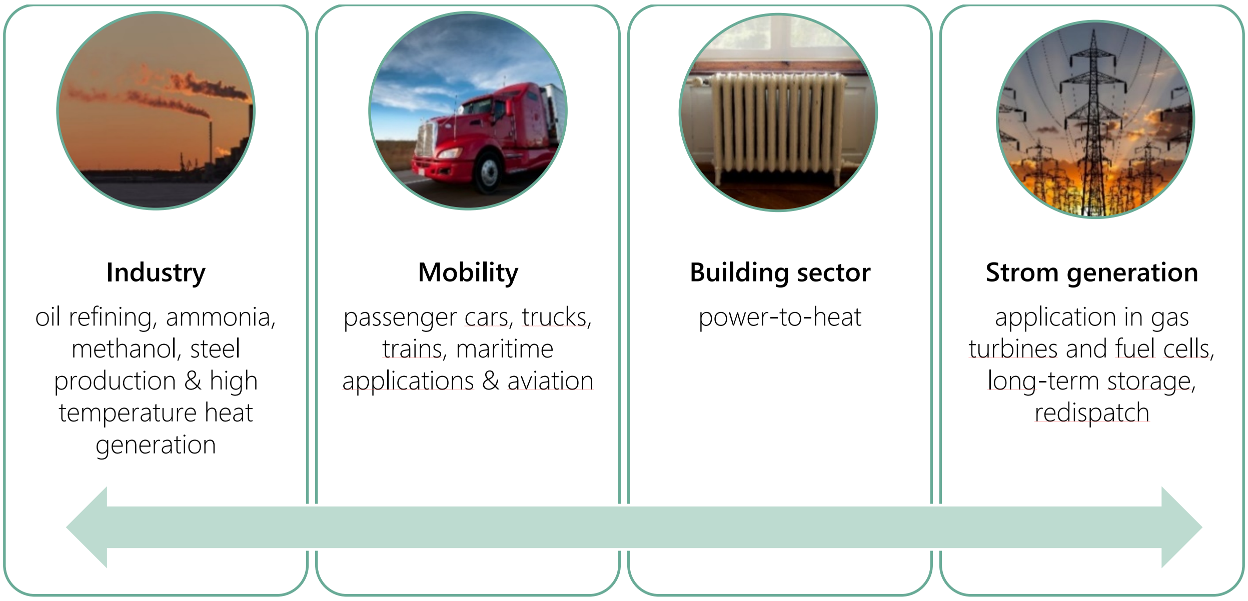

Figure 7: Cross-sector hydrogen applications

Industrial sector

The four most important single applications of hydrogen currently are in oil refining (33 %), ammonia production (27 %), methanol production (11 %) and steel production through direct reduction of iron ore (3 %). Future growth depends on the development of demand for downstream products, in particular refined fuels for transport, fertilisers for food production and construction materials for buildings. (International Energy Agency 2019)

Today, more than 60 % of the hydrogen applied in refineries is produced from natural gas (grey hydrogen). Stricter air pollution standards could increase the usage of hydrogen in refineries by 7 % to 41 Mt/y by 2030, although further policy changes to curb rising oil demand could dampen the pace of growth. Current global refining capacity is generally considered sufficient to meet increasing oil requirement, meaning that the majority of future hydrogen is likely to originate from existing plants already equipped with hydrogen production units. This suggests that retrofitting CCS might be a suitable option to reduce associated emissions. (International Energy Agency 2019)

Demand for ammonia and methanol is expected to grow in the short to medium term, with new capacity providing an important opportunity to expand low-emission hydrogen pathways. Higher efficiency can reduce overall demand, but this will only partially offset growth. Whether via natural gas with CCS or electrolysis, the technology is available to meet the additional hydrogen projected for ammonia and methanol production (from 44 Mt/y today to 57 Mt/y by 2030) in a low-carbon manner. As a priority, substituting any further coal-based production without CCS with low-emission pathways would contribute significantly to emission reductions. (International Energy Agency 2019)

In the longer term, the steel industry and high-temperature heat generation offer enormous potential for the application of green hydrogen for decarbonisation. Provided that the technological challenges that currently stand in the way of widespread introduction of hydrogen in these sectors can be overcome. In the long term, it should be technically feasible to produce all primary steel with hydrogen, but this would require huge amounts of renewable electricity (about 2,500 TWh/year, i.e. about 10% of today's global electricity generation) and would only be economic at very low electricity prices without policy support. Steel demand is projected to increase from 4 Mt H_2/year to about 6% by 2030. (International Energy Agency 2019)

Transport sector

Beyond existing industrial utilizations, hydrogen and its derivatives have long-term applications in many areas, including mobility. Figure 8 shows the different mobile hydrogen TRL levels. The transport sector is characterised by a high energy consumption (a total of 36,078 GWh in 2018 in Germany) as well as a limited possibility of electrification. At the same time, only 5.7 % of this energy was of renewable origin (BMWi 2018). Hydrogen can be employed in modified combustion engines, the predominant energy converter in road transport today. However, the most important application for the future is assumed in the fuel cell.

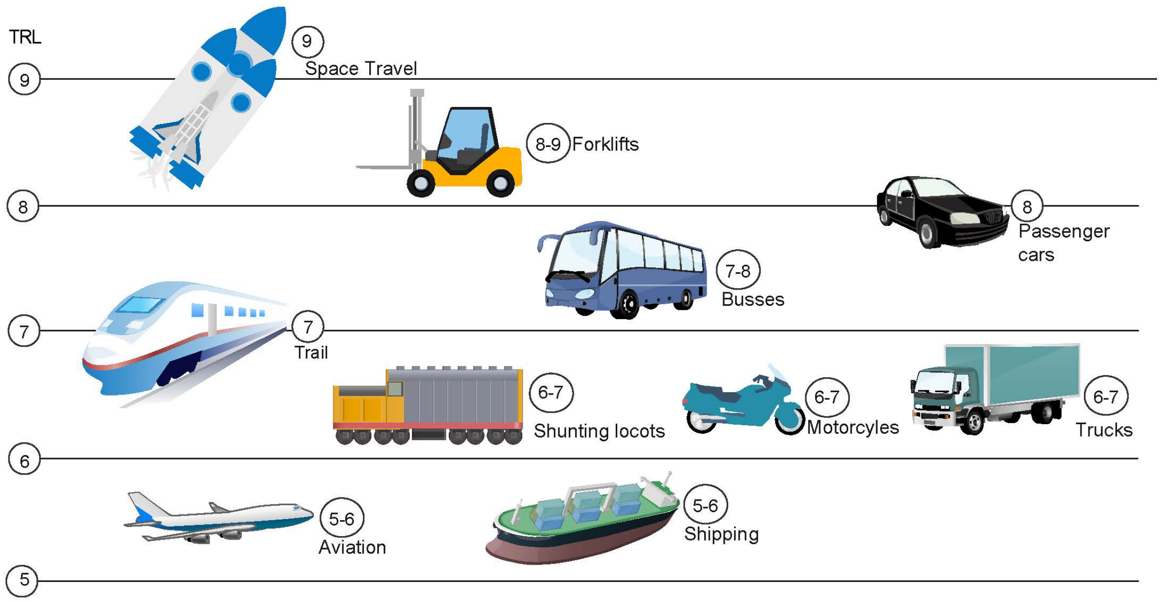

Figure 8: Technology maturity levels (TRL) of mobile hydrogen applications

Fuel cell vehicles (FCEVs) are particularly interesting for road transport. There are about 12,000 light commercial vehicles worldwide, mainly in California, Japan and Europe. In addition, about a thousand hydrogen-powered buses and trucks are tested in demonstration projects. As the global vehicle population is expected to continue to grow, hydrogen could capture part of this market. The competitiveness of hydrogen FCEVs in transport depends on the cost of fuel cells and the construction and use of refuelling stations. For cars, the main issue is to lower the cost of fuel cells and hydrogen storage in the vehicle. As a result, they could compete with battery electric vehicles at ranges of 400-500 km and attract consumers who value range. For trucks, the priority is to lower the delivery price of hydrogen. (International Energy Agency 2019)

Regulatory approaches already exist aiming to increase green power-based fuels in the long term. The Clean Vehicle Directive (Directive (EU) 2019/1161) is worth mentioning. This promotes environmentally friendly mobility solutions in public tenders. The directive defines "clean vehicles". For light commercial vehicles, emissions are limited to a maximum of 50 g/km CO_2 and up to 80 % of the applicable limit values for NO_x and PN in real driving conditions until 2025; from 2026, the definition only applies to zero-emission vehicles. Additionally, heavy-duty vehicles are supposed to be operated only with alternative fuels including hydrogen. Furthermore, the directive sets national targets for public procurement. For Germany, a minimum share of 38.5 % of clean vehicles has been set. (European Parliament & Council 2019) A corresponding H_2 filling station infrastructure must be established in advance. Currently, 95 H_2 filling stations are in operation in Germany and 7 are under construction. With these figures, Germany is the second country after Japan with the largest hydrogen refuelling station infrastructure. By 2030, the market ramp-up should be ensured with a network of 1000 H_2 filling stations. (H2 Mobility 2022)

In August 2022, the world's first fleet of hydrogen-powered passenger trains started operation in Lower Saxony between Buxtehude, Bremerhaven and Cuxhaven, according to the Landesnahverkehrsgesellschaft Niedersachsen. At the official start on 24 August 2022, five trains were initially in operation, with the other nine to be added by the end of the year. (Dirk Altwig et al. 2022) Considering that rail is a main mode of transport in many countries, hydrogen trains could be most competitive in rail freight transport by creating regional routes with low network utilisation and cross-border freight traffic. (International Energy Agency 2019)

In shipping and aviation, where only limited opportunities are available for the application of low-carbon fuels, hydrogen-based propulsion systems represent the only decarbonisation option according to current knowledge. However, compared to oil-based fuels (diesel, paraffin), their production costs are currently still very high. In aviation, green hydrogen in the form of electricity-based liquid fuels (power-to-liquid) is also a possible alternative to biofuels, which are only available in limited quantities due to their land requirements, also raise major questions about the sustainability of bioenergy and, as a result, are at least insufficient for a complete decarbonisation of the transport sector. (International Energy Agency 2019)

Excursus: Shipping

Renewable energy sources are supposed to be employed in shipping in the long term. In 2018, global maritime transport caused more CO_2 emissions than Germany as a whole. (Federal Environment Agency 2022) In figures, this is 1.076 million tonnes of CO_2 equivalents and 2.76 per cent of global greenhouse gas emissions. (DNV 2022)

In turn, the International Maritime Organization (IMO) adopted measures to counter the projected increase in emissions. In a 2018 agreement among member countries, greenhouse gas emissions ought to be reduced by 50 % by 2050. However, more far-reaching measures must be implemented to reach the targets of the Paris Climate Agreement. However, some countries refused in 2021 to establish zero-emission, climate-neutral shipping by 2050. A new revision of the targets is scheduled for 2023. (Clean Shipping Coalition 2021) In the European Union's Fit for 55 legislative package, shipping is included in the EU Emissions Trading Scheme (ETS). (European Commission 2022) In the summer of 2022, the European Parliament voted that the shipping sector should receive a separate ETS (ETS II) together with the transport and building sectors. This agreement developed in the Fit for 55 negotiations in the trialogue between the Council, Commission and Parliament. The proposal still lacks the votes of the member states and of the entire parliament. (Tagesspiegel 2022)

The conversion of ship propulsion systems poses challenges for the industry. While drives of smaller passenger ferries, motorboats and inland waterway vessels, for example, could also be electrified, this is not readily possible for ships of greater power or range. These include above all seagoing vessels such as tankers, cruise ships and container ships or additionally coasters and RoPax ferries. The current fuels marine diesel and heavy fuel oils must be replaced by climate-friendly alternatives. The application of liquefied natural gas (LNG) and methanol also offers little alternative. The reduction in emissions here is only between 15 and 25% and 10% respectively. (DNV 2021) Power-to-X products will therefore be indispensable as fuels in the future. These include hydrogen (pressurised, liquid, stored in carrier oils (LOHC)), ammonia, methanol, synthetic diesel and synthetic natural gas (SNG). In addition to internal combustion engines, fuel cells in combination with electric motors are also possible as propulsion engines.

The various drive technologies - based on renewable energy sources - still differ significantly in their degree of technical maturity. Hydrogen can already be utilized today in dual-fuel combustion engines as well as in fuel cells. Pure hydrogen combustion engines are expected in the next two years. This is primarily a possible alternative for private and work boats or smaller ferries. Methanol-fuelled combustion engines are already on the market for years. Currently, methanol fuel cells are also tested in demonstration projects. Ammonia is another promising fuel. At present, numerous projects are concerned with the development of combustion engines. Exhaust gas purification is of particular importance, as the amount of climate-damaging nitrogen oxides emitted must be kept low. Synthetic methane - like natural methane - can already be applied in ship engines. However, it is important to reduce the methane slip. Unburnt SNG that escapes from the engine and enters the atmosphere is 28 times more harmful to the climate than CO_2. (MAN 2022)

The multitude of possibilities already points to one of the challenges. Hydrogen and each of its derivatives exhibit advantages and disadvantages, so that none has yet emerged as a clear favourite. Not all of them are equally suitable for powering the various types of ships with their differing operational profiles, routes and sizes.

This is primarily due to the volumetric energy density of the media and the specific storage technology on board. To give an example, a cubic metre of hydrogen compressed to 700 bar carries about only a third of the energy as the same amount of ammonia. Accordingly, pressurised hydrogen takes up much more space on the ship. This is not a knock-out criterion for passenger ferries or inland vessels that have regular access to a bunkering infrastructure, but it is for seagoing container ships.

Engine and fuel cell development, as well as weighing up which medium is applied on which type of ship, are not the only challenges. Sustainable shipping is currently hindered above all by the low availability of PtX products as fuels and their high prices. (DVZ 2022) In view of a ship's service life of several decades and the associated high investment costs, the decision for an alternative propulsion technology is a long-term one. Conversion to another type of propulsion is sometimes technically difficult and often not economically feasible. To circumvent this, the subsequent use of alternative fuels should already be considered during the design and construction of ships.

There are also still open points in terms of regulation. Since the individual substances are very different in their aggregate state and hazard potential, there are no uniform rules and standards. For some derivatives, they have yet to be developed. (Esfeh et al. 2022; McKinsey & Company 2022) Safe handling also requires training and further education of the ship's crew and port personnel.

Another challenge for international maritime transport is the availability of fuels in the ports of destination. The lower energy density of hydrogen, ammonia and methanol also reduces the range of the ships if the tank size remains the same. If larger fuel tanks are installed, this in turn reduces the cargo volume. For climate-friendly shipping, it is therefore becoming increasingly important to adapt ships to their routes. (DNV 2021) Green corridors" are a possible solution. These are important trade routes along which emission-free shipping can develop. Important stakeholders include shipping companies, fuel producers, cargo owners, regulatory and port authorities as well as classification societies. The first Green Corridors could then have positive spill-over effects on the rest of the transport sector. (Getting to Zero Coalition 2021) At the UN Climate Change Conference in Glasgow, 22 nations, including Germany, already signed a declaration to establish at least six corridors by 2025. (UN Climate Change Conference UK 2021)

Building sector

Another discussed employment path is the building or heating sector, whether in fuel cell heating systems or by direct combustion instead of natural gas. Hydrogen is only utilized to a very limited extent as an energy source in the global building sector today, although various possible applications are tested. For efficiency reasons, however, heating buildings by applying heat pumps or heat grids is preferable (BUND 2016). Where this is not possible (e.g., in densely populated residential areas and commercial buildings), the use of hydrogen-based heating systems might be an option. (Sterner 2017)

Electricity sector

In an energy system based on renewable energies, hydrogen can provide a resilient power supply. Consequently, a dunkelflaute, i.e. a longer phase of reduced wind and solar power generation, can be intercepted by reconverting previously stored green hydrogen into electricity in gas turbines or fuel cells. (Stecherle et al. 2020) In addition, ammonia could be co-fired in coal-fired power plants in the short term to reduce CO_2 emissions.

As a bridging technology, partial feed-in into the existing natural gas grid is possible. The application of electrolysers to serve the grid has short-term advantages in view of the slow expansion of the grid. If there are currently peaks in electricity generation due to high levels of solar radiation and wind, renewable energy plants are temporarily shut down (so-called redispatch) to prevent grid overload. In addition to the lack of efficiency, this is very cost-intensive, as operators whose plants are regulated must be compensated by the transmission system operators (TSOs). (International Energy Agency 2019)

1.6 Costs of hydrogen

The three most important factors influencing the production costs of green hydrogen are

- the cost of electricity from renewable energies (electricity procurement costs),
- the capacity costs of the electrolysers, which include investment and financing costs of the electrolysers
- as well as the achieved capacity utilisation.

The biggest cost factor for green hydrogen is electricity purchase costs, even though these already declined due to the competitive use of renewable energy. In some cases, green hydrogen can already achieve cost competitiveness with fossil hydrogen at ideal locations with the lowest cost of electricity from renewable energy sources. (Andreas Gelfort et al. 2022) At constant electricity prices, the higher the number of full-load hours, the lower the hydrogen production costs. According to a cost estimate by the Wuppertal Institute for Climate, Environment and Energy and DIW Econ, a megawatt hour of green hydrogen could be produced in this country with onshore wind power for 146 to 231 euros, with offshore wind power for 178 to 282 euros due to the higher electricity prices, and with photovoltaics for 253 to 344 euros due to the lower number of full load hours. (Wuppertal Institute and DIW Econ)

Due to larger production plants and a reduction in average investment costs, an improvement in efficiency and improved utilisation rates, capacity costs could already decreased so much by 2030 that electricity purchase prices, with a share of more than 85 %, will be by far the most important cost factor. (Gao et al. 2022)

Options to produce green hydrogen are discussed in the draft of the Delegated Act Red II. The current design of the criteria for renewable electricity procurement needs to be revised so that the multitude of requirements does not become a showstopper for the ramp-up of the hydrogen economy. (Andreas Gelfort et al. 2022)

The price index "Hydex" of E-Bridge Consulting GmbH is available for orientation for possible purchase prices for grey, blue and green hydrogen.

The Hydex is a cost-based price index. It reflects the average price of hydrogen derived from a steam reformer (with and without CO_2 storage) or electrolyser in Germany. The Hydex considers the short-term production costs of hydrogen (see Figure 9). Capital costs are not included.

- The "Hydex Green" indicates the average price for hydrogen ex site of an electrolyser. Green electricity certificates are procured for the entire electricity volume. It is assumed that, in accordance with the EnWG and the EEG amendment, no grid fees, EEG levy and electricity tax are incurred for the electricity purchased for electrolysis.
- The "Hydex Blue" indicates the average price for hydrogen ex site of a natural gas steam reformer if the released CO_2 is captured and stored accordingly (so-called CCS). For this process, ETS emission allowances only must be procured for the remaining emissions.
- The "Hydex Grey" indicates the average price of hydrogen ex site of a natural gas steam reformer. For the CO_2 released, emission certificates must be procured within the framework of the ETS.

The natural gas steam reformer is connected to the natural gas grid. Average grid charges for the gas connection of industrial customers are assumed. The Hydex refers to the (lower) calorific value of hydrogen.

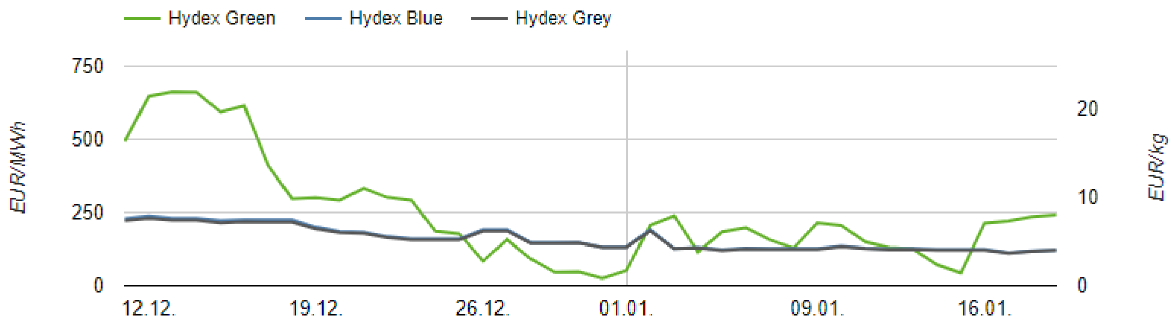

Figure 9: Hydex - Hydrogen Index last 30 days (as of 19.01.2023)

1.7 Hydrogen market - outlook

Hydrogen demand in Germany and worldwide

In Germany, the future hydrogen demand is estimated at 90-110 TWh in 2030 within the framework of the national hydrogen strategy (Federal Ministry for Economic Affairs and Energy (BMWi) 2020), where the consumption of hydrogen in 2020 was between 55-60 TWh. Various studies assume a hydrogen demand of about 270 TWh in 2050. In correspondence to this number, 31 % will be produced in Germany. The remaining hydrogen will be imported (Philipp Gerbert et al. 2018; Bründlinger et al. 2018; Now GmbH 2018b; Fraunhofer 2019). According to the coalition agreement, 10 GW of generation plants for water electrolysis are supposed to be installed by 2030 to meet the increasing demand, with a focus on domestic production (SPD, ALLIANCE 90/THE GREENS, FDP 2021). The current consumption of grey hydrogen is to be replaced in the long term by CO_2-neutral hydrogen.

The European expansion targets envisage a total capacity of 40 GW by 2030 (see Table 3). Some countries around the world also announced ambitious expansion targets for water electrolysis. Chile intends to build a total of 25 GW of generation capacity by 2030. In Australia, several projects involving water electrolysis and, in some cases, further processing into ammonia were already announced to meet global demand. According to the IRENA study, to limit global warming to below 2 °C, 270 GW of total capacity for water electrolysis would have to be installed worldwide as early as 2035. According to McKinsey's study "The Global Hydrogen Flows Perspective", the world is expected to need 660 million tonnes of hydrogen by 2050 to achieve carbon neutrality. (McKinsey & Company 2022)

Table 3: Explicit expansion targets for water electrolysis until 2030; (International Renewable Energy Agency (IRENA) 2021)

	Country	Expansion target in GW
EU	Germany	10,00
	France	6,50
	Italy	5,00
	Spain	4,00
	Netherlands	3,50
	Portugal	2,25
	Poland	2,00
	Other EU strategy	11,75
South America	Chile	25,00

General importance of the import of hydrogen

This outlined large demand for hydrogen-based energy sources in Germany, but also in Europe as a whole, as well as Japan and South Korea as further important demand regions, will not be able to be covered by domestic production alone or, according to the McKinsey study, will not be able to cover their entire demand at competitive costs. (McKinsey & Company 2022). In addition to building a strong domestic production landscape, imports from both Europe and non-European countries will play an important role.

Different trade flows for hydrogen could emerge - pure hydrogen is a "neighbourhood" business, i.e. hydrogen can be sourced predominantly domestically or via pipelines from nearby regions and only then shipped. If these options are not available, hydrogen derivatives could be shipped globally; transport costs are low and production costs depend primarily on the availability of resources such as CO_2 and iron ore.

Global trade in hydrogen and derivatives, including hydrogen carriers, ammonia, methanol, synthetic paraffin and green steel (which uses hydrogen in its production) can significantly reduce the total investment and system costs required - investment in long-distance transport and trade represents less than 20% of total investment, but is key to achieving significant savings, including $5 trillion in total system costs across the supply chain.

Importance of importing hydrogen by ship

The study further states that considerable shipping capacities are needed for the transport of hydrogen, its derivatives and important raw materials such as CO_2. With a view to importing by ship, additional 1,100 ships will be required by 2050 to enable maritime trade in hydrogen and its derivatives. This corresponds to about 75% of the current global fleet of 1,500 liquefied natural gas (LNG) tankers. Existing ammonia and methanol ships could initially be reused and synthetic paraffin and green steel pellets could be transported using existing tankers and freighters. Over time, these existing vessels would need to be replaced with newly built vessels. To enable the shipment of exports and imports of hydrogen and its derivatives, global port tonnage for hydrogen carriers needs to be increased to more than 2,000 million tonnes. This is about three to four times the capacity of the ports of Rotterdam or Singapore. In the major existing ports, much of the import infrastructure for green steel and most derivatives could be reused, although capacity expansion for methanol and ammonia would probably be required. New port capacity is needed for new supply areas in remote locations.

2 Market analysis of the city of Cuxhaven and surrounding area

2.1 Location analysis

The district of Cuxhaven is the northernmost and largest district in Lower Saxony in terms of area, with the natural borders of the North Sea, the Elbe and Weser estuaries. The district is divided into 29 municipalities, with 7 unitary municipalities and 3 joint municipalities (Figure 10). Cuxhaven as the district capital of the district of the same name is the third largest city on Lower Saxony's North Sea coast. It belongs to the metropolitan region of North-west and Hamburg. The latter is one of the large independent cities in Germany and lies at the mouth of the Elbe into the North Sea.

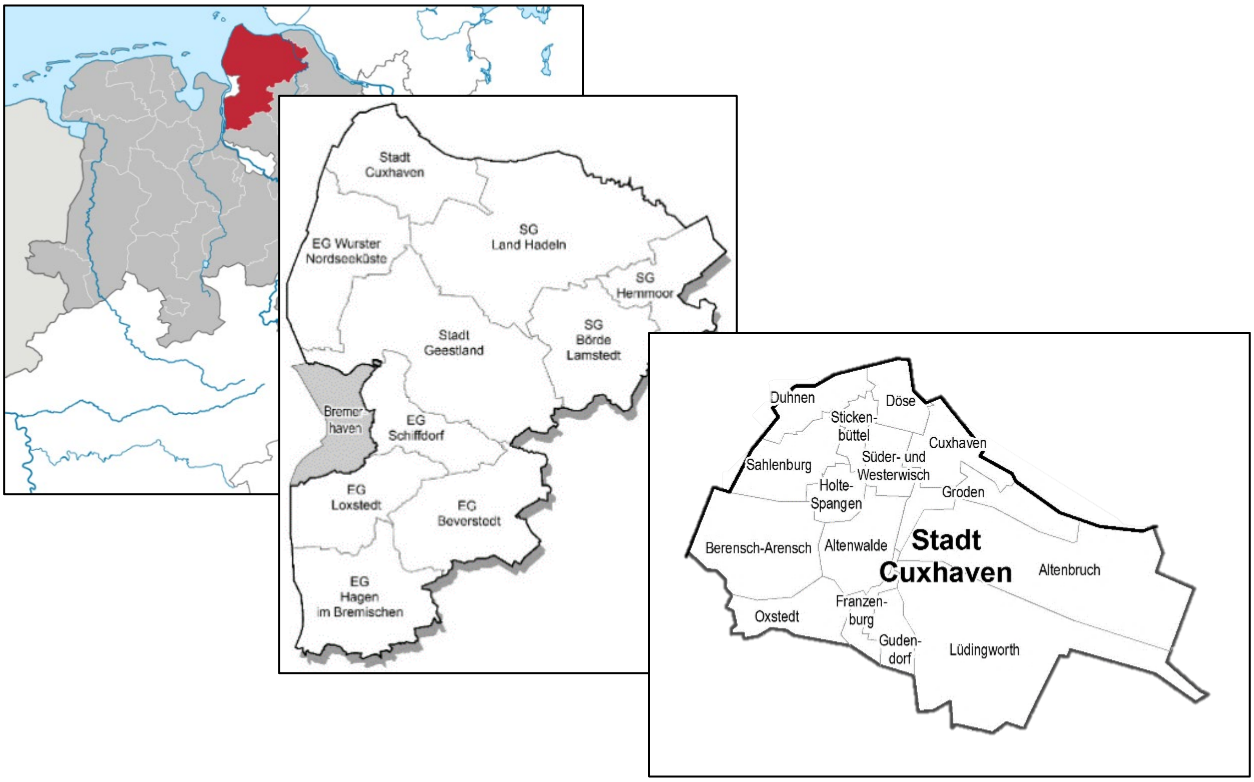

Figure 10: f. l. t. r. Location of Cuxhaven County in Lower Saxony, County of Cuxhaven © County of Cuxhaven 2016, Municipality of Cuxhaven © County of Cuxhaven 2016

In order to assess the potential of the city and region of Cuxhaven in the field of hydrogen and to highlight synergies with other locations, a site analysis is carried out below. For this purpose, the connections to the gas and electricity grids, the heat supply and the land and water transport connections are examined in detail.

2.1.1 Electricity infrastructure and application of renewable energies

The Cuxhaven region is connected to the 110 kV power grid (high voltage) of the grid operator Avacon Netz GmbH. Substations in and around the city of Cuxhaven include Stickenbüttler Weg, Industriestraße, Ottendorf and Spieka (Figure 11). The 110 kV high-voltage lines (yellow) and the 380 kV extra-high voltage line (purple) are shown. The yellow dots represent the transformer stations. The left-hand side shows the region of north-eastern Lower Saxony between the Weser and Elbe rivers. On the right-hand side, the Cuxhaven region is shown enlarged.

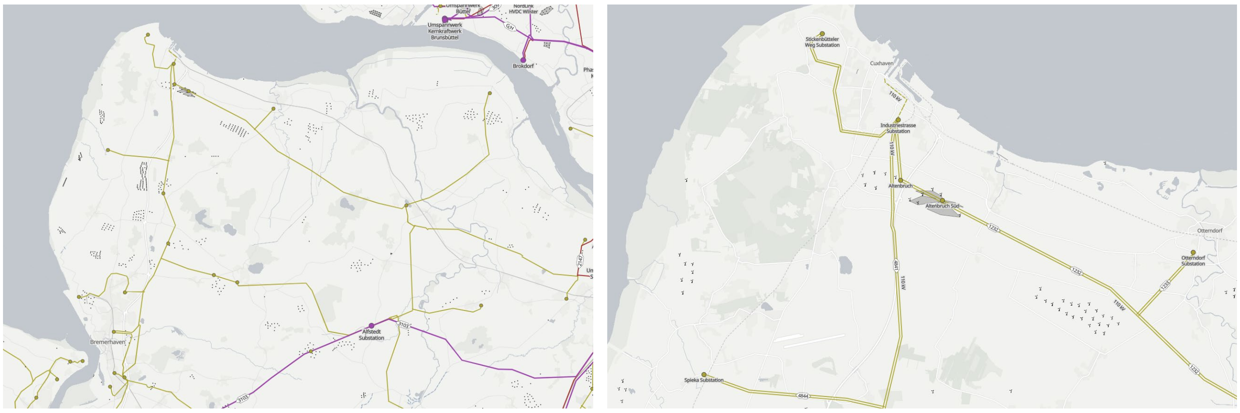

Figure 11. Schematic representation of the region's electricity grid. (Open Infrastructure Map 2022)

The Marktstammdatenregister is the register for the German electricity and gas market in which, above all, master data on electricity and gas generation plants as well as master data of market players such as plant operators, grid operators and energy suppliers are registered. Cuxhaven exhibits the data listed in Table 4. The onshore installed wind power plants with a total of ~67,160 kW and the self-generation of solar power through small photovoltaic plants with a total of ~11,773 kW play an important role in electricity generation. The expansion of the application of biomass with currently 695 kW through a wood-fired power plant with 17 MW capacity is currently under construction. Other gases and natural gas are employed with a total of 1,057 kW installed capacity in CHP units and 894 kW installed capacity in mini and micro CHP units. Thus, the share of electricity generation from renewable energies in Cuxhaven is 97.6 % (79,628 kW) and the share from fossil fuels is 2.4 % (1,953 kW).

Table 4. Installed systems (without storage) according to the Marktstammdatenregister, rounded to kW (postcode areas: 27472, 27474, 27476, 27478; as of 01.12.2022).

Energy source	installed capacity	attachments	in planning/under construction
Biomass	695 kW	3	17 MW (wood-fired power plant)
Other gases	1,058 kW	3; thereof 2 = 526 kW	20 kW (1 plant)
Natural gas	895 kW	49; thereof 1 >50 kW	-
Solar radiation energy	11,773 kW	766, of which 2≈750 kW	151 kW (23 individual plants)
Wind	67,160 kW	25; thereof 23 >2000 kW and 3 <500 kW	-
Total	81,581 kW		17,171 kW

Figure 12 shows the installed wind turbines (WT) and solar plants larger than 300 kW. The plants directly belonging to the city of Cuxhaven are outlined in red.

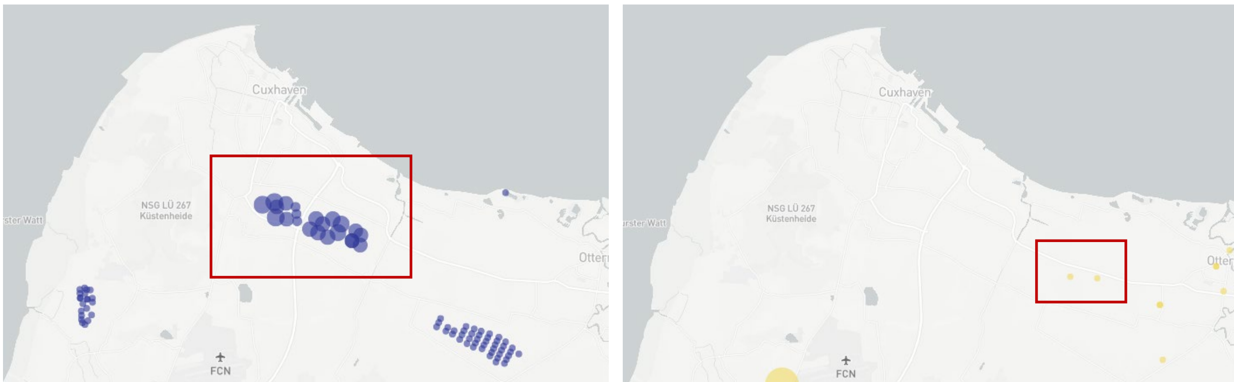

Figure 12: Installed wind turbines (left); installed solar systems (right) (own representation)

2.1.2 Gas infrastructure

Gas infrastructure (onshore)

The operator of the local natural gas supply network in the city of Cuxhaven is EWE Netz GmbH. A section of the local gas network is shown in Figure 13. This network is fed by the long-distance gas pipeline ETL-69 coming from Bremerhaven, which is operated by Gasunie Deutschland Transport Services GmbH. The transition from pipeline ETL-69 to the local supply network is located at the depot of EWE Netz GmbH in Humphry-Davy-Straße 41 in Cuxhaven.

A future connection of Cuxhaven to the "European Hydrogen Backbone" network (see section 1.4 d) is not planned - even according to the current status of the national gas network development plan until 2050.

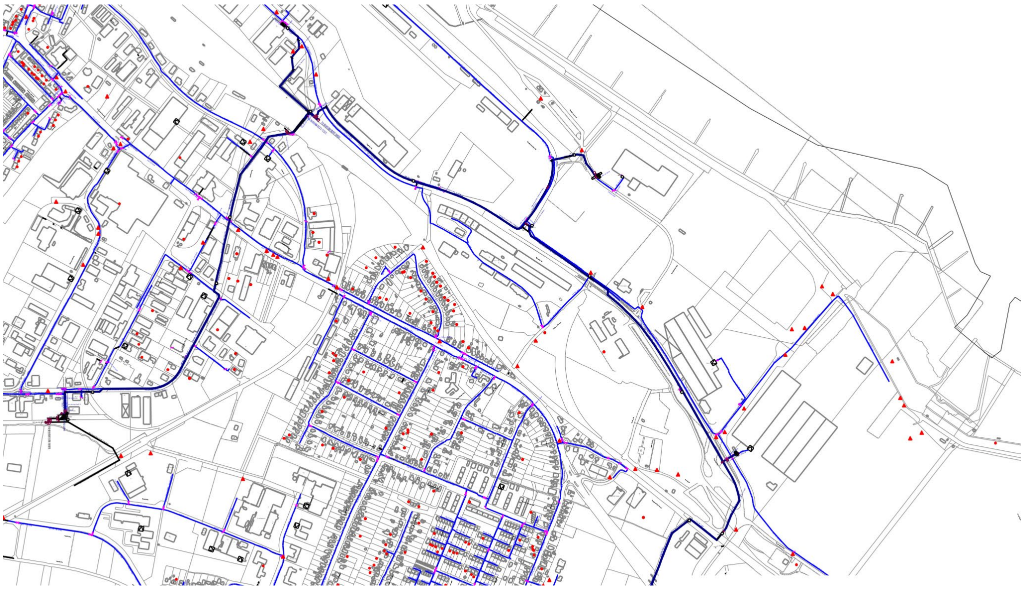

Figure 13: Section of the local gas supply network (E.W.E. AG 2022)

Gas infrastructure (waterside)

There are currently no natural gas pipelines in the immediate vicinity of Cuxhaven. In the wider catchment area of the German Bight, the Europipe I/II with landfall in Dornum and the Norpipe with landfall in Emden are worth mentioning (see Figure 14).

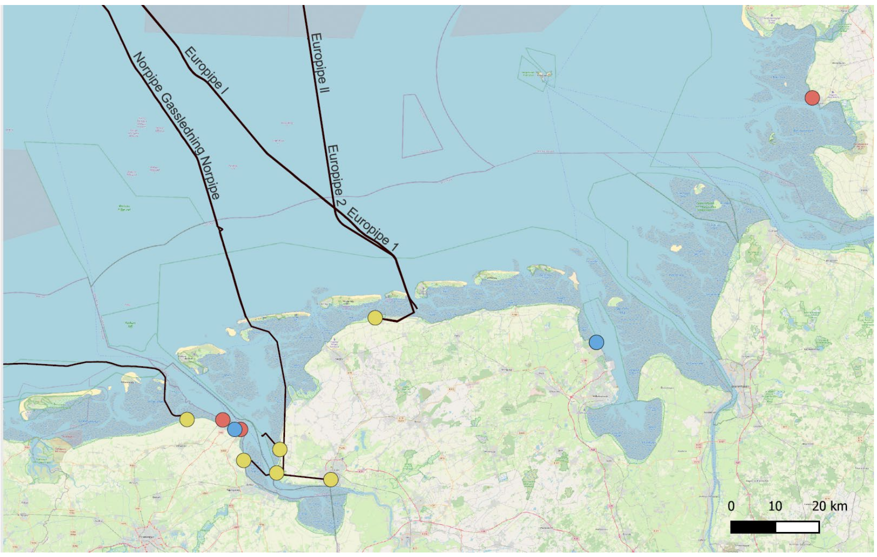

Figure 14: Pipelines in the North Sea, blue dots represent landing points for LNG, red dots represent landing points for electricity, yellow dots represent landing points for gas (own representation)

By 2035, the construction of a pure hydrogen pipeline called AquaDuctus of the AquaVentus project family is planned, which is to be dimensioned for the hydrogen transport of 1 million t/a to the mainland. According to the plans, the hydrogen produced in the German Entenschnabel by means of offshore wind energy will pass Helgoland and land on the northern shore of the Elbe estuary (Figure 15). (GASCADE Gastransport: AquaDuctus 2022)

Landing of natural gas transported by ship via floating or fixed terminals is currently not planned for Cuxhaven.

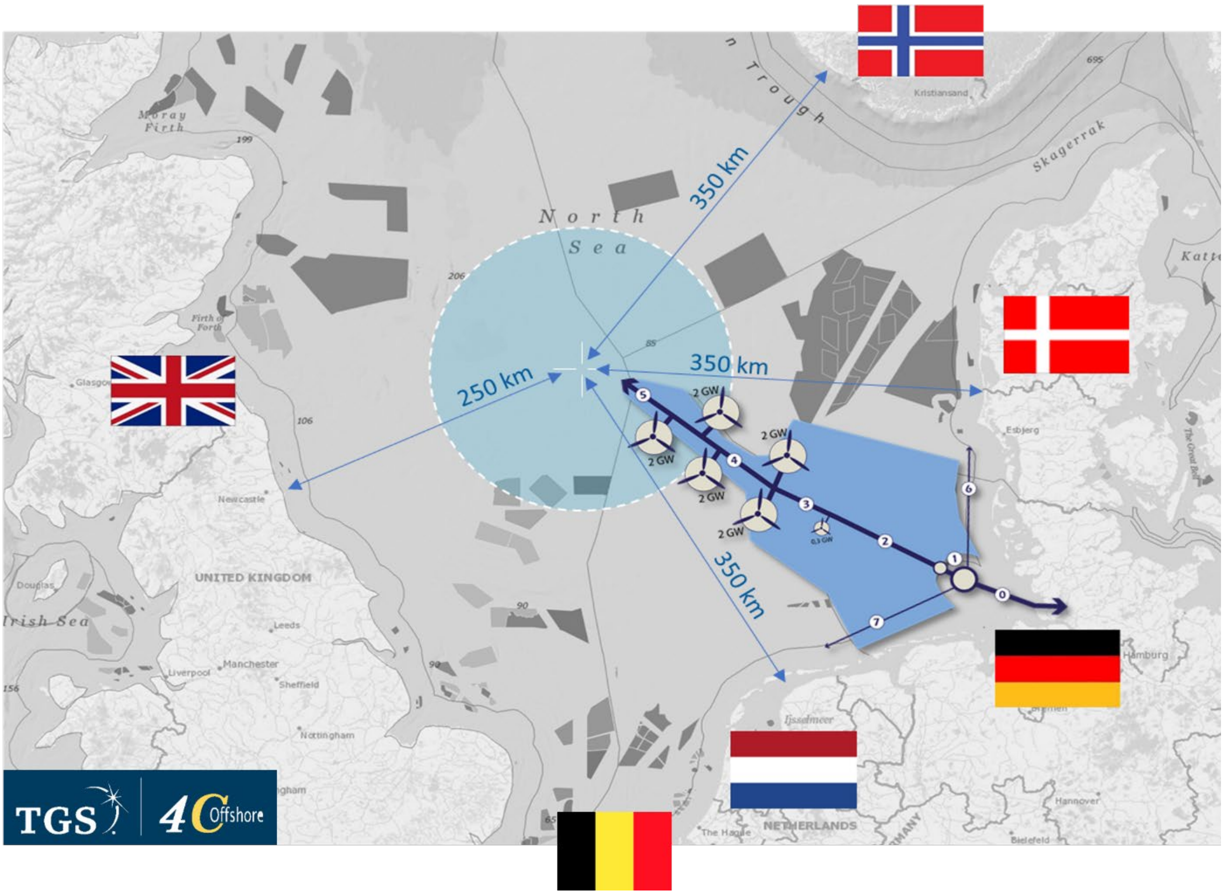

Figure 15: Representation of the planned hydrogen infrastructure in the North Sea (AquaVentus plans in blue, schematic course of a possible pipeline in dark blue) ©4cOffshore

Cavern storage under Cuxhaven

Caverns could represent a possibility for large-volume storage of gaseous hydrogen. These already existing underground natural gas caverns in Germany could be converted to hydrogen storage, according to information from the National Hydrogen Council. The first natural gas cavern storage facilities in Etzel (East Frisia) and Rüdersdorf (Brandenburg) are already tested for hydrogen storage with positive partial results. (Teuffer 2022)

For Cuxhaven and the surrounding area, several underground salt and clay rock layers were analysed in the past for the storage of natural gas or as a repository for highly radioactive waste. These underground rock layers were formed in different geohistorical phases. Some of these salt rock layers display vertical deformations towards the earth's surface, which are simplified in this report as salt domes. Existing salt domes and clay layers in the vicinity of Cuxhaven are shown in Figure 16.

To apply these layers as hydrogen storage, several vertical cavities are flushed into the salt or mudstone layer, depending on the required storage volume. The production of a single cavern storage facility takes about 2 to 5 years. With current capacities of storage caverns, construction and operating costs are far below those of above-ground pressure reservoirs. Further advantages of cavern storage are a low surface area requirement, a high storage density of up to over 200 bar and high storage capacities. Salt stone caverns are considered to be particularly well suited for the storage of hydrogen, as they can be described as technically tight and thus only extremely low losses of approx. 0.015 % are expected. For this reason, salt stone caverns could be a particularly safe storage option for hydrogen.

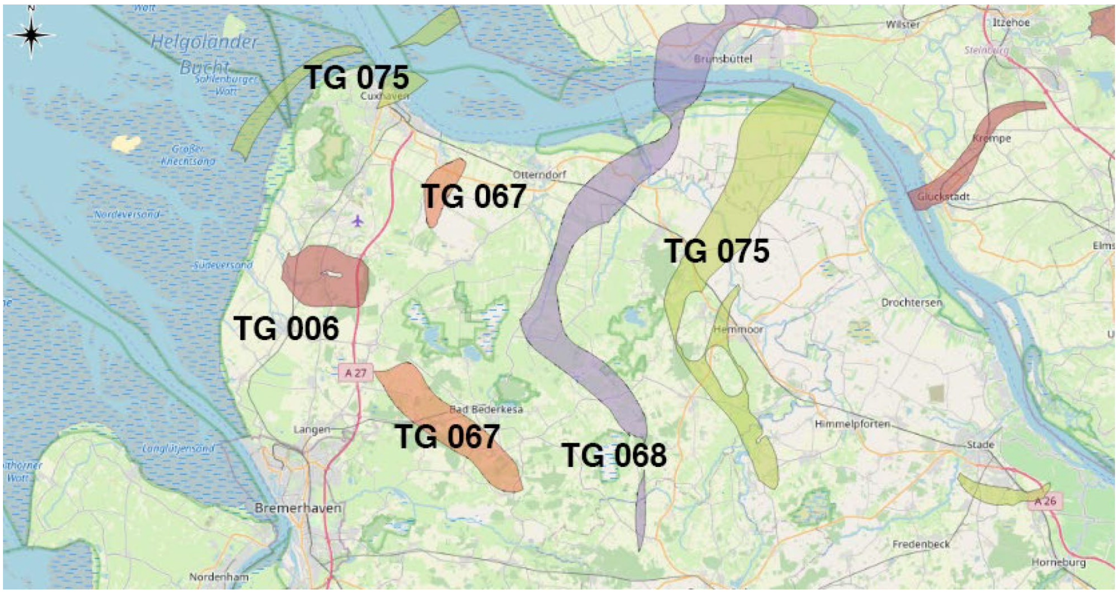

Figure 16: Geographical location of the clay and crystalline rock sub-areas. (Saleem Chaudry 2022)

Three sub-areas of the rock salt layer TG 075 are located at a depth of 640 to 1500 m below sea level (NHN) below the city of Cuxhaven and the offshore Elbe estuary. These parts of TG 075 would have the potential to be used as local hydrogen storage in the form of storage caverns. The clay rock layer TG 006, located south of the airport Sea-Airport Cuxhaven & Nordholz, is at a depth of between 400 and 1500 m below sea level. A connection from Cuxhaven to TG 006 and both parts of TG 067 would increase the storage volume in case additional storage is needed. TG 068 is a rock salt layer stored at a depth of 730 to 1500 m below sea level. (Saleem Chaudry 2022)

It should be noted that none of the rock strata shown in Figure 16 has yet been developed as a cavern. A fundamental investigation for the storage of hydrogen and testing of different pressure levels would be required.

2.1.3 Heat supply

The heat demand in the Cuxhaven area in 2017 was 866,740 MWh and 94.4 % was provided by fossil fuels such as natural gas (69 %), heating oil (17 %), coal (8 %) and LPG (0.4 %). Only 5.1 % was covered by renewable energy sources. The heat supply is implemented individually on site by households and industrial and commercial enterprises using the above-mentioned energy sources.

There is currently a sewing heat network in the harbour, which will be fed once the wood-fired power plant starts its operation. With the completion of the wood-fired power plant, a district heating network is to be established (Cuxhaven wood-fired power plant 2023). The possibilities of using waste heat from industrial processes, e.g., from electrolysers, in existing and new buildings were discussed with the cooperative "Wohnstätten Cuxhaven" during a stakeholder dialogue on 05.01.2023.

2.1.4 Transport infrastructure

The transport infrastructure is an essential component for the development of the city of Cuxhaven and the surrounding region. This chapter examines at Cuxhaven's existing infrastructural connections.

Supra-regional road network

Cuxhaven is connected to Bremerhaven and Bremen via A27 and to Stade and Hamburg via B73 (see Figure 17).

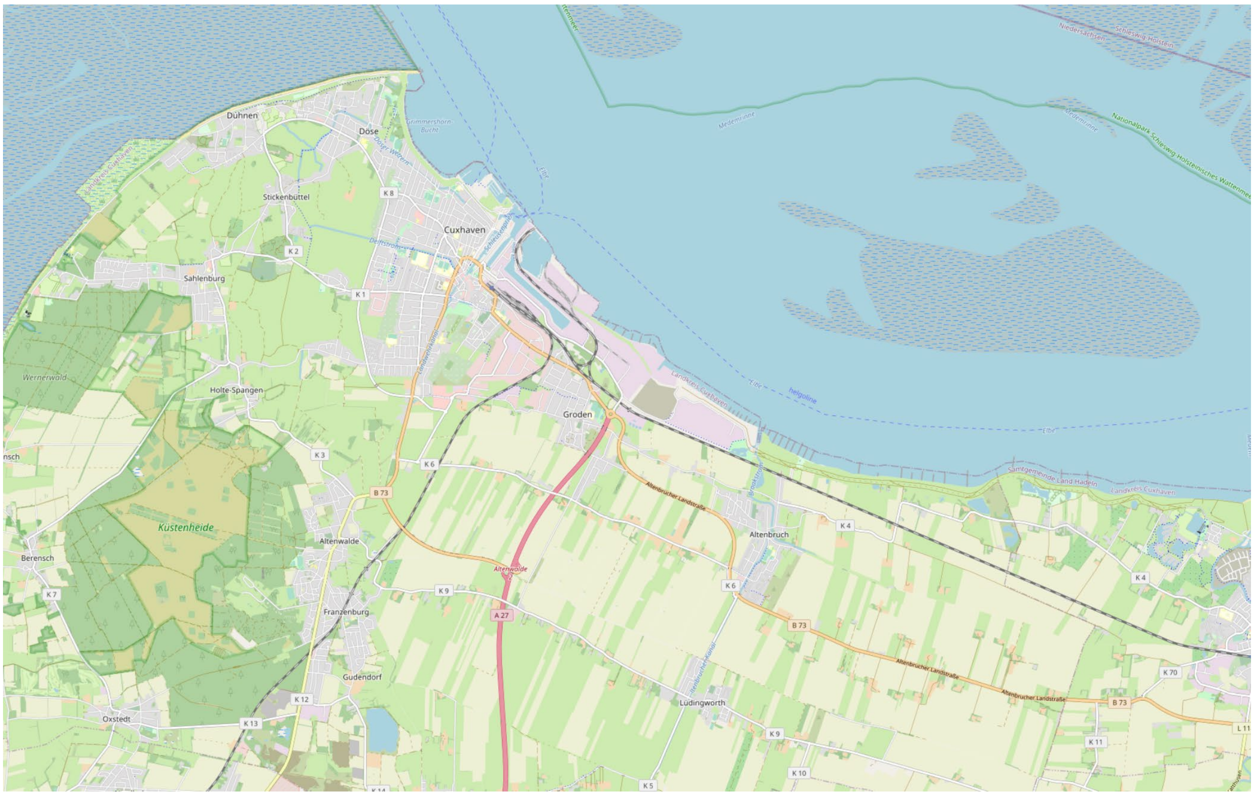

Figure 17: Overview map of Cuxhaven (Open Street Map 2022)

Public Transport

The Cuxhaven transport area is part of the mobility services offered by KVG Stade GmbH & Co KG. This extends between Cuxhaven, Bremerhaven, Hamburg and Soltau. City line services are operated in Buxtehude, Cuxhaven, Lüneburg, Stade and Winsen (Luhe) as well as intercity, school and professional services in the districts of Cuxhaven, Harburg, Lüneburg, Rotenburg (Wümme) and Stade. The city line network of Cuxhaven is displayed in Figure 18.

According to the mobility services group, the latest models of bus manufacturers with various alternative forms of propulsion (hybrid, hydrogen, fuel cell, rechargeable battery) have been tested at several KVG locations for several years in order to gain information about reliability, range and operational suitability. A successive procurement of vehicles with alternative propulsion systems is planned for the next few years. (KVG Stade GmbH & Co KG 2021a)

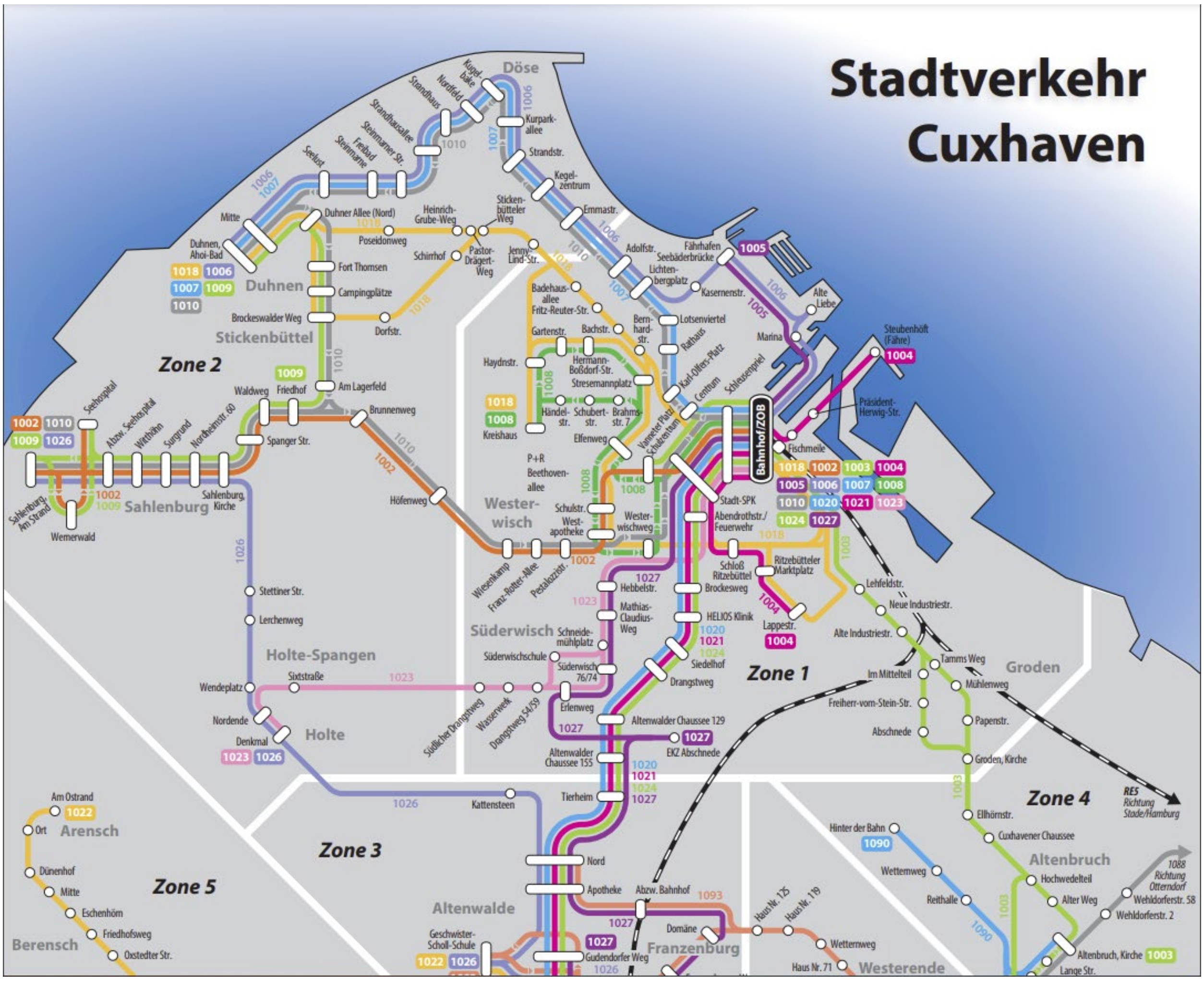

Figure 18: Cuxhaven city line network (KVG Stade GmbH & Co. KG 2021b)

Rail network

Cuxhaven is connected to Bremerhaven via the single-track, non-electrified train line no. 1310 (DB 125). Almost exclusively diesel-powered public transport trains of the so-called "Nordseebahn" run on this line. In rare cases, goods trains run on the line, which means that individual trips of the hourly scheduled Nordseebahn have to be cancelled. (Academic 2022)

In Bremerhaven, line no. 1310 is connected to the double-track, electrified line no. 1740 (DB 125) to Bremen. There is thus a direct rail connection between Cuxhaven and the Maschen marshalling yard, which is important for freight traffic. (Academic 2022)

In direction Hamburg, Cuxhaven is also connected via train line no. 1720 (DB 101.3). This line is only electrified between Stade and Hamburg. (Academic 2022) Continuous electrification and a two-lane expansion are planned by 2032.

In addition, 14 hydrogen-powered passenger trains will be operated on the existing rail network between Buxtehude, Bremerhaven and Cuxhaven from the end of 2022 onwards (see also Section 1.4 "Transport sector").

Within Cuxhaven, there is another train line between line no. 1720 and Steubenhöft in the Amerikahafen. This line serves the connection of the Amerikahafen and is split several times on the terminal site.

Shipping

As shown in Table 5 the following scheduled ferries and excursion ships that arrive and depart from Cuxhaven are currently in operation:

Table 5: Overview of the scheduled ferries and excursion ships in Cuxhaven

Designation	Field of application	Fuel
MS Flipper	passenger ferry to Neuwerk Island	diesel
MS Helgoland	passenger ferry to Helgoland	LNG, diesel (1-5 % of total fuel)
MS Flipper	seal banks, Kiel Canal	diesel
MS Atlantis	seal banks, harbour tours	diesel
MS Otter	harbour tours	diesel
MS Störtebeker	seal banks, harbour tours	diesel
Jan Cux	seal banks, harbour tours	diesel
Jan Cux II	seal banks, harbour tours	diesel
Adler Cat	passenger ferry to Hörnum/Sylt	diesel
Halunder Jet	passenger ferry to Helgoland	diesel

Aviation

The Sea-Airport Cuxhaven & Nordholz has the following characteristics (Flughafen-Betriebsgesellschaft Cuxhaven/ Nordholz mbH):

- Second longest runway in Lower Saxony (2,439 m)
- All-weather capability, night flying capability
- Connection to the A27
- Situated directly on the approx. 40 ha Sea-Airpark Cuxhaven/Nordholz commercial and industrial estate
- Germany's largest naval aviation base
- Areas of operation: Cargo transport, business flights, offshore services, working and research aviation projects, flights to Helgoland.
- Perspective: Establishment of a land base for the airborne supply of the offshore wind farms in the North Sea

2.1.5 Port infrastructure

The port of Cuxhaven (DECUX) is one of the largest multi-purpose ports in Germany and is located on the southern bank of the Elbe river estuary. Port operators are Niedersachsen Ports GmbH & Co. KG, the largest port operator on the German North Sea, and Cuxport GmbH. Further operators are Blue Water BREB GmbH, Titan Wind Energy (Europe) A/S, EnTec Industrial Services GmbH & Co. KG and the Machulez group of companies.

German Offshore Industry Centre Cuxhaven

An important component of the port is the German Offshore Industry Centre Cuxhaven (DOIZ). The purpose of the DOIZ is to build and ship all the necessary components for offshore wind turbines. The centre was realised with the support of the state of Lower Saxony. Over the last few years, a total of more than € 600 million euros from private and public funds were invested in the expansion of the DOIZ infrastructure. For Europe, the DOIZ is increases its importance as the expansion continues. In addition to the onshore infrastructure, there are various quay facilities specifically designed for heavy transport, handling and storage of offshore wind cargo. Part of the offshore terminals are, among others, a heavy load platform with a permissible maximum area load of 90 t/sqm, a gantry crane with a safe working load (SWL) of 500 t as well as a logistics area of more than 5 ha with a permissible maximum area load of 25 t/sqm. Roads in and around the DOIZ are also specially designed for heavy-duty transport. (DOIZ 2022)

Terminal infrastructure

The port of Cuxhaven offers special terminals for the loading, unloading and storage of RoRo (roll-on roll-off) cargo, containers, offshore wind project cargo, heavy lift cargo, bulk cargo and general cargo. An oil or gas terminal is not available or planned to date. All terminal areas are equipped with drainage systems and electrical supply for terminal lighting. The port currently offers a total of six berth zones (LP 1-4, LP 8-9), while an additional three berths (LP 5-7) are in the process of realisation to close the gap between berths LP 4 and LP 7. After completion of the harbour extension, a continuous quay length of just under 4 km is to be created in the future. The state of Lower Saxony has recently pledged 100 million euros for this expansion. (NDR 2023).

Furthermore, additional land-based logistics and industrial areas are being planned. The fishing port and marina are not considered in detail in this report, as they offer neither the required infrastructure nor free areas for hydrogen landings or terminals. Existing and currently planned berths and terminal areas of the seaport of Cuxhaven are shown in the following Figures 19-21 and Figure 22.

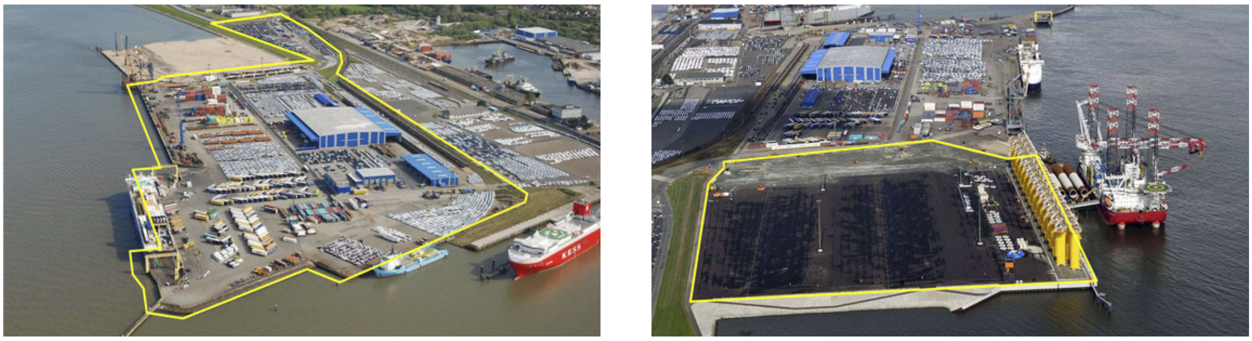

Figure 19: LP 1-3 - multi-purpose terminal (left), LP4 - offshore/ heavy lift/ multi-purpose terminal (right). (offshore-basis.com 2022b)

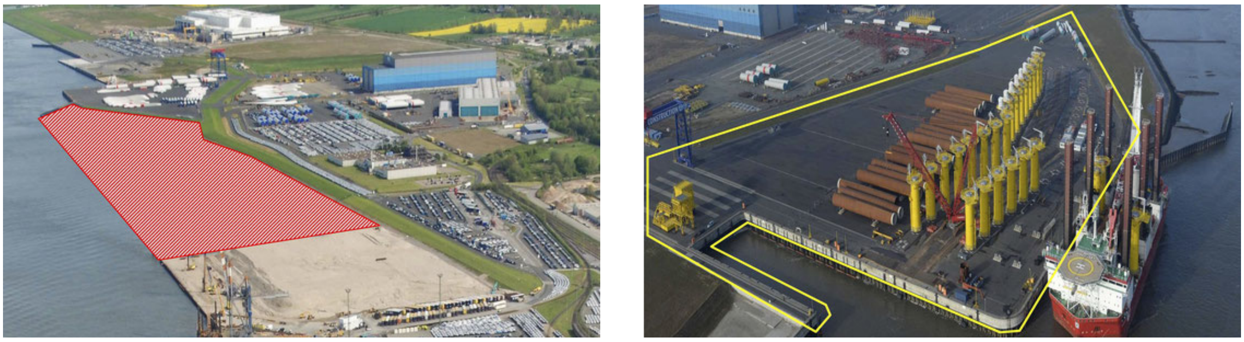

Figure 20: LP 5-7 (left), LP 8 - "Terminal I" offshore terminal (right). (offshore-basis.de 2022b)

Figure 21: LP 9 - "Terminal II" offshore terminal (left), LP 9.3 (right). (offshore-basis.de 2022b)

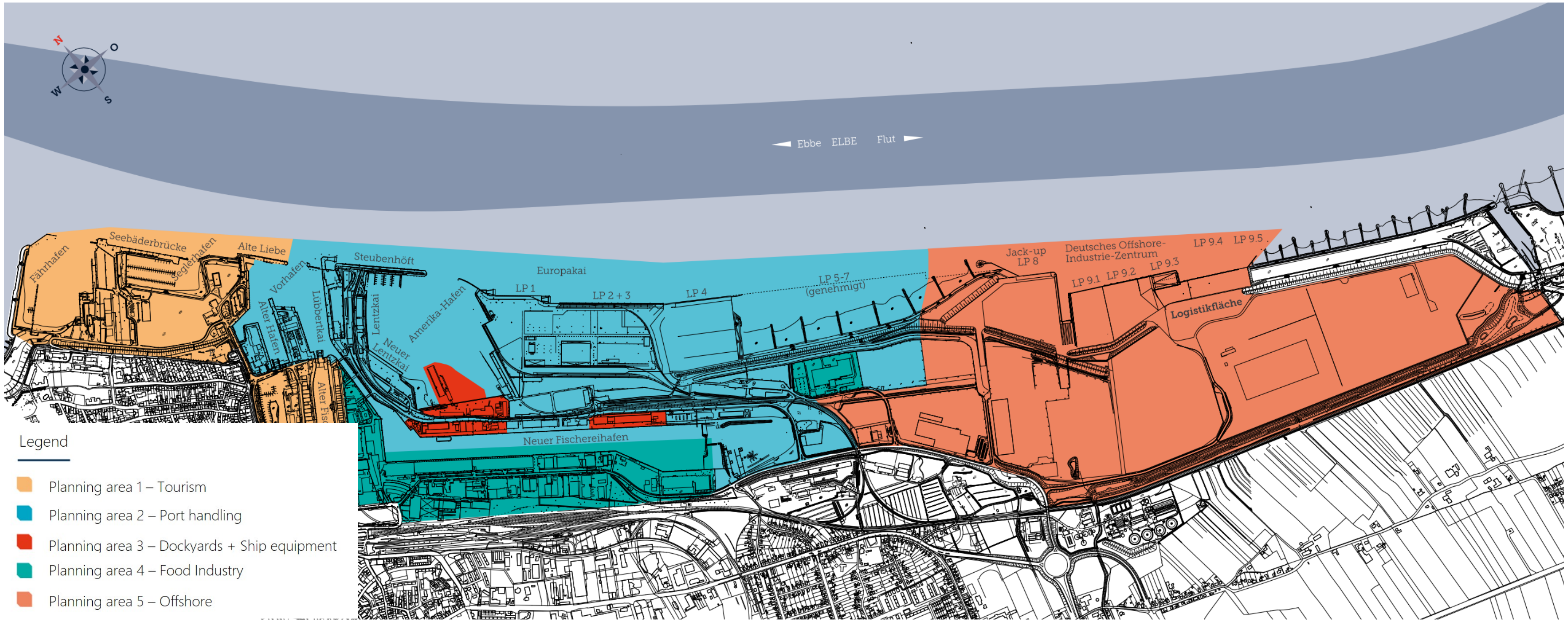

Figure 22: Overview of port terminals and berths (Niedersachsen Ports 2019)

Berth	1-3	4	5-7	8	9
Designation/Status	European quay Multipurpose	Multi-purpose incl. jack-up vessels	in planning	"Terminal I" offshore projects	"Terminal II" offshore projects
Quay length	1.025 m	240 m	1.257 m	376 m	734 m
Max. Draught	15,19 m	15,4 m	14,5 m	12,7 m	12,7 m
Total area	319 ha	8.5 ha	28 ha	11 ha	12 ha
Facilities	2 RoRo ramps, gantry cranes, port rail crane	Heavy load area, sufficient draught for jack-up vessels		650 t gantry crane, heavy load area, waiting berth and berth under gantry crane	Heavy load area, 1 RoRo ramp

Restrictions in relation to ship dimensions

The current dredging depth of the Elbe generally allows a tidal draft of 12.80 - 15.10 m upstream and 12.80 - 13.80 m downstream. These restrictions depend on whether a vessel is moving with or against the tidal surge along the Elbe. Further restrictions on the Elbe are a maximum total length of vessels of 400 m and a width of 60 m. (Lower Saxony Ports 2021)

The possible ship dimensions in the port of Cuxhaven are limited by the water levels of the Elbe, the length of the berths and the dredging depth of the berths. The average tidal range at the Cuxhaven site is 2.94 m and the necessary "Under Keel Clearance" (UKC) is 1 m. (Lower Saxony Ports 2021)

Industrially usable areas near the port

An overview of vacant and planned industrial sites is provided by Figure 23. The sites are divided into three successive development steps. 95 % of the areas developed in the first and second steps are already allocated to companies such as Cuxhaven Steel Construction GmbH, AMBAU GmbH, Siemens Gamesa Renewable Energy AG, Nordmark GmbH and Titan Wind Energy (Europe) A/S. Areas still available in this step are divided into two sub-areas and are displayed in Figure 24:

- area B: 1.9 ha
- area D: 4.0 ha

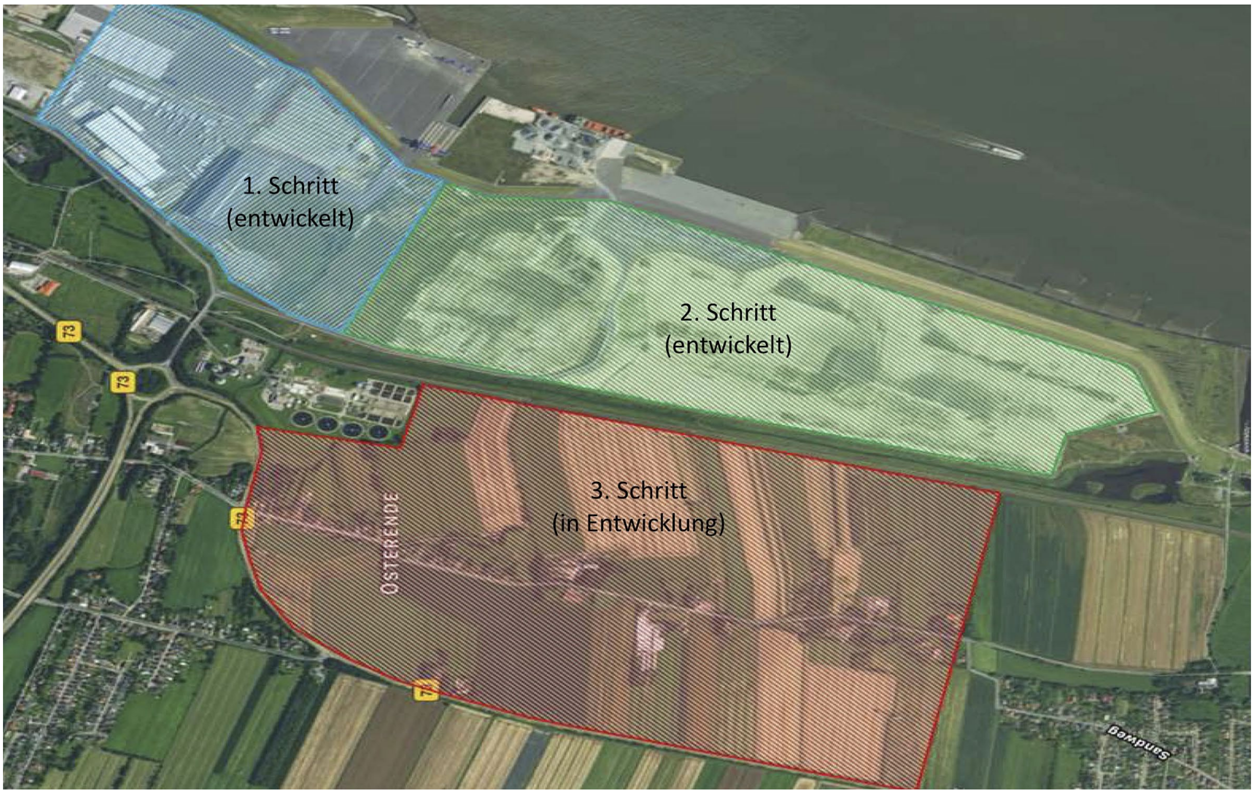

Figure 23: Industrial development areas in Cuxhaven (offshore-basis.de 2022a)

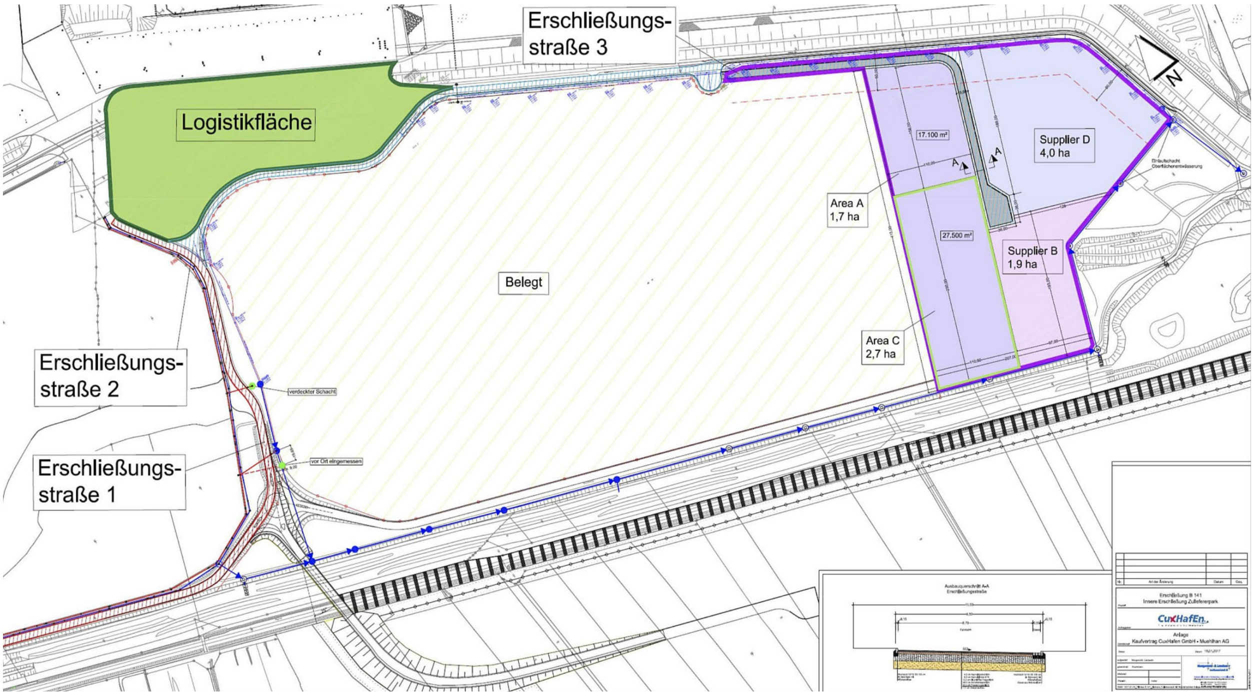

Figure 24: Vacant development areas in Cuxhaven in the 2nd step. (offshore-basis.de 2022a)

2.2 Hydrogen market analysis of the city of Cuxhaven and the region

The starting point for the hydrogen market analysis is an overview of all previous and current projects on the topic of hydrogen in Cuxhaven and the region (see section 2.2.1). Based on this, key players are identified (see section 2.2.2) and plans and developments to date in the hydrogen field are analysed (see section 2.2.3). This information is supplemented by results from interviews and workshops in which current evolutions in the hydrogen field are discussed, possible obstacles are highlighted and impulses are gathered (Section 2.2.4).

2.2.1 Hydrogen projects

The status quo of hydrogen projects is recorded below in the form of profiles. (AquaVentus 2022; Alstom 2022; EWE 2022; Wintershall DEA 2022; ifh Göttingen 2022; IHK Lüneburg Wolfsburg 2022; KONGSTEIN 2021; Ile-Region Moorexpress-Stader Geest 2020; German Offshore Industry Centre Cuxhaven 2022).

Project:	**AquaVentus**
Actors:	Around 100 companies, research institutions and organisations
Goals:	▪ 10 gigawatts of green hydrogen generation capacity from offshore wind energy and production of 1 million tonnes of green hydrogen via electrolysis technology by 2035 plus transport on land ▪ Long-term integration into a European hydrogen network
Results:	Feasibility studies
Funding:	IPCEI, TransHyDE
Timeline:	2020 - 2035

Project:	**Energy island**
Actors:	SMT GmbH, Büro Elbstrom, Marc Itgen and the Agentur für Wirtschaftsförderung Cuxhaven, Jörg Singer
Goals:	Feasibility study for the construction of an energy island in the Elbe estuary
Results:	Concept for an energy island
Funding:	no details
Timeline:	no details

Project:	**Hyways for Future**
Actors:	EWE as consortium leader, over 100 players in the network
Goals:	Activation of the hydrogen value chain in the mobility sector in the Northwest: ▪ Building up electrolysis capacities ▪ Creation of a nationwide network of hydrogen refuelling stations ▪ Investments in bus fleets, collection vehicles, trucks and cars
Results:	Letters of intent with around 16 partners for the acquisition of 60 fuel cell vehicles in Cuxhaven
Funding:	Funded with up to 20 million euros via the HyLand programme (BMDV)
Timeline:	2020 - 2024

Project:	**H2Move**
Actors:	iGas Energy, EnTec, Wintershell dea, Turneo
Goals:	Development of a hydrogen infrastructure in Cuxhaven: ▪ Construction of a 2 MW electrolyser (expansion to 20 MW) ▪ Conversion of the Mittelplate supply fleet to hydrogen hybrid propulsion ▪ Construction of a hydrogen refuelling station for landside application
Results:	Implementation phase
Funding	Funded within the framework of Hyways for Future and half by the federal and state governments (total 14-million-euros)
Timeline:	2022 - 2024

Project:	**H2Skills**
Actors:	Chamber of Commerce Braunschweig-Lüneburg-Stade, Chamber of Commerce Lüneburg Wolfsburg
Goals:	Identification of further training needs in the hydrogen economy within the framework of expert interviews and an online survey with all companies in north-eastern Lower Saxony (Celle, Cuxhaven, Harburg, Heidekreis, Lüchow-Dannenberg, Lüneburg, Osterholz, Rotenburg (Wümme), Uelzen, Stade and Verden).
Results:	Initial approaches for certificate courses, additional examinations, further training offers and supplementary modules to existing qualification offers
Funding:	Funded by the European Social Fund (ESF) in the framework of REACT-EU initiative
Timeline:	2021 - 2023

Project:	**OffsH2ore**
Actors:	PNE, Fraunhofer ISE, Kongstein, Silicaa, Wystrach
Goals:	Concept study for offshore hydrogen production applying offshore wind energy as an isolated solution ▪ Design of a 500 MW offshore H_2 production platform ▪ Technical system concept ▪ Techno-economic analysis
Results:	Technical plant concept for offshore hydrogen production in connection with a ship-based transport concept for compressed hydrogen
Funding:	Sponsored by the BMWK
Timeline:	2020 - 2022

Project:	**Hydrogen mobility through biowaste fermentation (WaMoBa)**
Actors:	Abfall-Service Osterholz, FAUN, H2NoN, Landkreis Cuxhaven, Landkreis Osterholz, Landkreis Verden, Stadt Cuxhaven,
Goals:	ecologically sustainable bio-waste recycling: ▪ Collection of biowaste by fuel cell vehicles and biogas production ▪ Reforming biogas into hydrogen and supplying collection and logistics vehicles through an H_2 filling station
Results:	Implementation phase
Funding:	Funded by H2.N.O.N with federal and state funds within the framework of ARTIE and the Joint Task "Improvement of the Regional Economic Structure" (GRW)
Timeline:	2020 - 2023

Project:	**Hydrogen trains in local passenger transport (Coradia iLint)**
Actors:	Alstom, LNVG, evb, Linde
Goals:	▪ Employment of hydrogen-powered trains on the line between Cuxhaven, Bremerhaven, Bremervörde and Buxtehude ▪ Hydrogen refuelling station to supply the trains in Bremervörde
Results:	Procurement of 14 hydrogen-powered regional trains
Funding:	Funded by the BMDV within the framework of the National Innovation Programme Hydrogen and Fuel Cell Technology
Timeline:	2016 - 2022

2.2.2 Actors

The currently relevant actors in Cuxhaven in the hydrogen field are listed in Table 6.

Table 6: Overview of hydrogen stakeholders in Cuxhaven

Actor	Focus
Agentur für Wirtschaftsförderung (AfW)	Investment promotion and advice
Alstom	Rail transport
AquaVentus e.V.	Offshore hydrogen
Berufsbildende Schulen Cuxhaven	Training
CARNEADES Project Services GmbH	Energy
Cuxhavener Elektromaschinen GmbH	Electric machines
Cuxhavener Kühlhaus GmbH	Services
Cuxport GmbH	Port
Deutsche Fischfang Union (DFFU)	Fishing
Deutsche Wasserstoff Liga e.V.	Association
DFDS Germany APS & CO. KG	Logistics
DHL local fleet	Mobility
Entec Industrial Services	Logistics services
Erneuerbare Energien Hamburg Cluster	Network
EWE Gasspeicher GmbH	Energy
EWE Wasser GmbH	Energy
Fairplay Schleppdampfschiffs-Reederei Richard Borchard GmbH	Shipping
FAUN Umwelttechnik GmbH & Co. KG	Mobility
Fraunhofer IFAM / Maritimes Testzentrum Helgoland	Research
FH Elsfleth	Research
H2.N.O.N	Network
Hafenwirtschaftsgemeinschaft (HWG) Cuxhaven e.V.	Maritime economy
Harren & Partner	Shipping
Hochschule Bremerhaven	Research
IDB Stadtsparkasse Cuxhaven	Housing industry
IHK Stade	Network
Institut für Innovative Logistik und Umwelt (ILU)	Research

Actor	Focus
Jade Hochschule, Elsfleth	Research
Karlson GmbH	Port
Kutterfisch-Zentrale GmbH	Fishing industry
Michael Habben truck & trailer	Commercial vehicles
Nautischer Verein Cuxhaven e.V.	Maritime
Niedersachsen Ports GmbH und Co. KG	Port
Niedersächsisches Ministerium für Wirtschaft, Verkehr, Bauen und Digitalisierung	Politics
OLEC Oldenburger Energiecluster	Network
Offshore-Safety-Trainingscenter Cuxhaven	Training
Otto Wulf GmbH	Maritime services
PNE AG	Energy industry
Sea Survival Center Cuxhaven	Training
Seefahrtschule Niedersachsen	Training
Siedlung Cuxhaven AG	Housing industry
Siemens Gamesa Renewable Energy	Offshore Wind
Stadt Cuxhaven	Politics
Turneo GmbH	Energy industry
Umweltmanagement AG (UMaAG)	Energy industry
Universität Bremen	Research
Unternehmensverband Cuxhaven Elbe-Weser-Dreieck e.V.	Network
Wintershall Dea	Energy industry
Wohnstätten Cuxhaven AG	Housing industry

2.2.3 Analysis of developments to date

In 2019 and 2020, two documents were elaborated to analyse hydrogen applications and develop a hydrogen strategy in Cuxhaven:

- Hydrogentle GmbH: Concept for hydrogen applications in Cuxhaven and the Elbe-Weser region; June 2019
- Kongstein GmbH: Hydrogen as part of the city of Cuxhaven's new DNA - Positioning 2020; further development of the hydrogen strategy for the city of Cuxhaven; March 2020

A breakdown of the assessments and recommendations is performed and the actual developments are provided below.

Concept for hydrogen applications in Cuxhaven and the Elbe-Weser region (June 2019)

The Hydrogentle GmbH concept, showing options in the area of production, distribution/storage and use of hydrogen, is first analysed (Hydrogentle GmbH 2019). Given that the options in hydrogen distribution and storage were kept general and no concrete details were described, here an analysis of the implementation is impossible. The proposed options for hydrogen production and applications are shown in Table 7 and are color-coded regarding their status (red: currently no initiative, yellow: in progress, green: implemented). Detailed explanations of the classification are illustrated below.

Table 7: Overview of the options in the "Concept for hydrogen applications in Cuxhaven and the Elbe-Weser region" and current status regarding their realisation

No.	Option	Details	Status of the implementation
1	H_2 from onshore wind	Combination of hydrogen production from onshore wind turbines and electricity purchase via a direct marketer (short-term)	red
2	H_2 from offshore wind	Hydrogen production from offshore wind (medium term)	red
3	Shore power supply for ships	Provision of the electricity required on board during port laytime by a shore-based fuel cell	red
4	Emergency power supply	Ensuring an uninterrupted power supply to critical facilities (cold stores, server stations or mobile phone systems) with fuel cells	red
5	Tourist ships	Conversion of fixed-route vessels to a hydrogen-based propulsion system	yellow
6	Industrial applications	Hydrogen deployment in energy-intensive processes	red
7	Waste heat utilisation	Waste heat utilisation of electrolysis for heating buildings	red
8	Sewage treatment plant	Application of the pure oxygen produced as a by-product of electrolysis in wastewater treatment plants	yellow
9	H_2 -filling station	Establishment of a hydrogen fuelling station to supply fuel cell vehicles (cars and trucks).	yellow
10	Mobility	Employment of hydrogen-powered	
		a) bus fleets (public transport)	red
		b) special vehicles (city cleaning and technical services)	yellow
		c) forklift trucks (port logistics)	red

Re No. 1: As part of the H2Move project, a 2 MW electrolyser is estimated to produce 1,000 kg of hydrogen per day starting in 2023. Water and electricity will be provided via the EWE grid, so electricity will not be sourced directly from onshore wind energy. Due to the Lower Saxony electricity mix and a local surplus of renewable energies in Cuxhaven, the electrolyser can be considered green in balance sheet terms. (Niedersächsisches Ministerium für Umwelt, Energie, Bauen und Klimaschutz 2020) In view of the planned expansion of the electrolyser capacity to 20 MW, onshore wind energy could play an important role in the electricity supply in the future.

Re No. 2: Currently, no offshore wind farms are planned in the relative vicinity of Cuxhaven for the onshore or offshore production of hydrogen. In 2013, the test field for offshore wind turbines built onshore was dismantled due to the expansion of the port and industrial site.

As a member of the AquaVentus Förderverein e. V., the Agentur für Wirtschaftsförderung (AfW) positioned itself to promote Cuxhaven's interests. In this context, the AfW is working to ensure that Cuxhaven establishes a supply port for the AquaVentus projects for the loading of offshore wind power modules or for the operation and maintenance of these turbines. In addition, Cuxhaven would be available as a landing point for the first container-based import of hydrogen.

At present, plans to establish an energy island in the Elbe near Cuxhaven with onshore/offshore wind turbines coupled with hydrogen production are in the concept phase (see 2.2.1 "Energy Island"). The AfW of the city of Cuxhaven commissioned an initial project outline for this. In addition, a master's thesis on the subject is currently completed.

Re No. 3: Given that Cuxhaven is the first port of the five Lower Saxony seaports of the operating company Niedersachsen Ports to offer a shore power supply (berth 9.3), this application of fuel cell could be of interest. Currently, electricity is drawn from the public grid. Possible alternatives are batteries, LNG and hydrogen. As shown in Table 8 the utilization of hydrogen as a mobile shore power solution is currently still at a disadvantage compared to the other technologies. This is due to currently still high CAPEX and OPEX costs and consequently high energy supply costs. Nevertheless, hydrogen as an energy carrier gains in importance and a TRL improvement as well as cost reductions ought to be expected.

Table 8: Overview of mobile shore power solutions (Hanseatic Transport Consultancy and MKO Marine Consulting 2022)

	Direct current	Battery	Hydrogen	LNG
Performance data	16.7 MWh	1.7 MWh/unit	500 kW/unit for 16 hours	1.3 MW/unit for 20 hours
TRL	7-8	7-8	4-5	7-8
CAPEX	0.7 - 1.5 m €	1.5 m €	> 2.0 m €	1.2 - 1.5 m €
OPEX	low	high	high	high
Energy supply costs	low	low	high	high
Maintenance costs	low	low	high	medium

Re No. 4: Stationary fuel cells can be applied for the uninterruptible supply or emergency power supply of critical infrastructures. This technology is already commercially available on the market and is being deployed, for example, at more and more locations for the emergency power supply of digital radio sites. Currently, analogous to the shore power supply of ships, there is no application in Cuxhaven. The reasons for this are not known. Conceivable causes are high investment costs for the conversion and the current scarcity of green hydrogen. Here, too, future cost reductions and the sufficient supply of green hydrogen could reduce the obstacles. A possible application could be hospitals in Cuxhaven.

Re Nos. 5, 8, 9: These three options were concretised in the H2Move project. Thus, an electrolysis plant with a capacity of 2 MW was installed to produce green hydrogen to supply the Mittelplate supply fleet, which is to be converted from diesel to hydrogen hybrid propulsion. Although the fleet is not involving tourism vessels as formulated in No. 5, this first practical, maritime application is intended to lay the foundation for a hydrogen infrastructure. Regarding this expansion the port and the entire region will benefit.

In addition, the produced oxygen as a by-product during electrolysis might be utilized in EWE's wastewater treatment plant.

Future plans include expanding the electrolysis capacity to 20 MW and supplying the hydrogen on land at a hydrogen refuelling station. Hydrogen would then be a fuel for buses, waste collection trucks, scooters, beach trains and cars. Later on, the hydrogen might supply crab cutters and other ships. (Wintershall DEA 2022; ifh Göttingen 2022)

Re No. 6: As mentioned in section 1.5, the conversion of energy systems in larger industrial plants (e.g., in the steel industry) from CO_2-intensive to emission-free processes employing green hydrogen offers great potential. Currently, hydrogen is not applied in the industrial companies located in Cuxhaven. The deployment of hydrogen in the DOIZ should be particularly examined.

Re No. 7: There are currently no ongoing hydrogen projects in the building sector in Cuxhaven. In order to estimate the future potential, an interview was conducted with the housing industry on 05.01.2023. Here, the potential of exploiting industrial waste heat, e.g., from electrolysers via district and local heating networks in existing and new buildings, was discussed. The stakeholder dialogue with the housing industry revealed a fundamental interest in covering the heat supply with heat grids.

Re No. 10: The implementation of hydrogen in the mobility sector is currently as follows:

a) Currently, no concrete plans for hydrogen-fuelled bus fleets are known (see section 2.1.4).

b) As part of Hyways for Future, the Agentur für Wirtschaftsförderung Cuxhaven signed letters of intent with around 18 partners for the procurement of 60 fuel cell vehicles. For example, the Cuxhaven Technical Services will replace a conventional waste collection vehicle with a fuel cell vehicle in the future. The fire brigade also plans to switch to fuel cell vehicles. (EWE 2022) Additionally, the mobility sector will be able to develop through the WaMoBa project (municipal waste disposal).

c) No projects are planned in the port logistics sector in Cuxhaven. Terminal tractors (TRL 7), empty container handlers (TRL 8) and industrial trucks (TRL 9) with fuel cell propulsion are available on the market. For cranes, no market-ready hydrogen-powered technologies are currently available. Market development is expected in the following 3-5 years. In the Clean Port & Logistics project funded by the BMDV, HHLA has set up a cluster to test hydrogen-powered equipment in port logistics. The aim is to support and accelerate the achievement of market maturity and integration into regular port operations (HHLA 2022). The results of this project could serve as a blueprint for the concrete deployment of hydrogen in Cuxhaven's port infrastructure. As a proportionate subsidiary of HHLA, Cuxport GmbH is directly involved in the cluster and is therefore informed about the results.

Hydrogen as part of the city of Cuxhaven’s new DNA - Positioning 2020 (March 2020)

In the document “Hydrogen as part of the city of Cuxhaven’s new DNA - Positioning 2020”, the local conditions of Cuxhaven were examined and the focus was placed on maritime applications and hydrogen production through offshore wind energy. Table 9 gives an overview of the developed suggestions and their implementation status (red: not commissioned, yellow: first approaches, green: implemented).

Table 9: Overview of the suggestions in “Hydrogen as part of the city of Cuxhaven’s new DNA - Positioning 2020” and current status

No.	Suggestions	Status of the implementation
1	Identification of two flagship projects and suggestion for implementation	
	a) Cuxhaven as an offshore H_2 landing point	green
	b) Ferry connection between Cuxhaven and Brunsbüttel	red
2	Suggestion to create a knowledge centre "Maritime Hydrogen" Cuxhaven and suggestions for existing stakeholders	yellow
3	Suggestion to develop a master plan	green
4	Recommendation on the integration of funding (no naming of specific funding programmes)	green
5	Identification of local support from politics, city hall, institutions, businesses and citizens.	green
6	Development of approaches for positioning and marketing hydrogen, maritime applications and offshore wind in Cuxhaven	green

Re Nos. 1a, 3, 4, 5: Within the framework of this master plan, Cuxhaven is examined as an offshore H_2 landing point. In addition, hydrogen projects and actors in Cuxhaven as well as specific funding opportunities are identified and an action plan is developed.

Re No. 1b: The ferry connection between Cuxhaven and Brunsbüttel is not addressed in the present study. The ferry connection could serve as a blueprint for a feasibility study.

Re No. 2: For the establishment of a knowledge centre, stakeholders were identified in the context of this Masterplan and brought together in an initial workshop (see section 2.2.4).

Re No. 6: In 2022**,** the DOIZ Cuxhaven was established at the suggestion of the then Minister for the Environment, Energy, Building and Climate Protection Olaf Lies. This master plan shows further approaches for the positioning and marketing of hydrogen, maritime applications and offshore wind in Cuxhaven.

2.2.4 Barriers and needs for the development of a hydrogen market

Based on a workshop with stakeholders from the city of Cuxhaven and the region, which was held in Cuxhaven on 17 November 2022, the developments to date and barriers to the establishment of a hydrogen market in Cuxhaven and the region were identified and requirements along the entire hydrogen value chain incl. further training & qualification were discussed.

According to the participants, challenges and obstacles are mainly in the following areas:

- Regulatory:
  - No certification of green hydrogen yet
  - No definition of green hydrogen at EU level yet
  - Inadequate funding concepts or extensive bureaucracy, especially in the SME sector, to be able to take advantage of funding programmes
- Techno-economy:
  - Market risks due to uncertainty in the industry (chicken-and-egg problem) and unresolved risk-distribution along the hydrogen value chain
  - Uncertainty about which specific hydrogen-based energy sources will prevail in which segment and the associated uncertainty in technology selection
  - Clarification of research needs and corresponding funding concepts
  - Specifically for port infrastructure: lack of technical solutions for special vehicles

With regard to the development of a hydrogen market in Cuxhaven, the following requirements were identified and proposals discussed:

Ideas from the group work on hydrogen production in Cuxhaven

The stakeholders identified the following points as necessary for the development of a commercially viable production of hydrogen in Cuxhaven:

- Pipeline connection to the gas transport network/gas transmission network
- Issuing a clear mandate for hydrogen production from wind power outside the EEG and accelerating the approval procedures for the construction of renewable energy plants, for the construction of infrastructure projects and for the construction of electrolysers
- Ensuring a constant purchase, e.g., through the acquisition of vehicles by the public sector (police, fire brigade, refuse collection) or through industry.
- Increasing the number of customers
- Overcoming the bottleneck of (large-scale) electrolyser production
- Expanding port infrastructure in order to be able to build more offshore wind turbines
- Using offshore wind power for green hydrogen production
- Clarifying of the uncertainty in shipping regarding hydrogen supply security ("What happens if electrolysers shut down, hydrogen cannot be produced and is therefore not available for refuelling?").
- Creating an infrastructure for research and research staff
- Establishing a pilot project with more than 70 MW electrolysis capacity
- Constructing an energy island in the Elbe estuary

- Using tourism to market the Cuxhaven region as an important component of offshore hydrogen production (e.g., via a showcase) and thus promoting the region as an attractive place to work

Ideas from the group work on hydrogen consumption in Cuxhaven

Regarding hydrogen consumption in Cuxhaven, the stakeholders considered the following points as prerequisites:

- Stakeholders advocate for the development of a concept for building a hydrogen economy that spans a 15-year period. Based on a 5-year interval, this would strengthen the long-term vision for the city.
- In addition, hydrogen prices must be lowered and financing instruments introduced to ensure attractiveness. In mobility area, the public sector should unlock the market by purchasing vehicles.
- Hydrogen should be prioritised for import and transport by pipeline versus ship should be analysed more closely. For this purpose, land must be secured and acceptance by the citizens must be fostered.
- In addition, a safe investment environment needs to be created to encourage potential suitors.
- The working group considers Cuxhaven to be a good location for a bunkering station for ships on their way to the Baltic Sea, for example, due to the draught of the harbour (more than 60,000 ship movements a year). (Wasserstraßen- und Schifffahrtsverwaltung des Bundes 2023)
- In addition, the stakeholders perceive the need for a connection to the hydrogen long-distance gas grid.

Ideas from the group work on further education & qualification in Cuxhaven

In addition to production and consumption, the educational landscape in Cuxhaven was discussed and analysed. Subsequently, questions were asked about the educational scenery in Cuxhaven. The stakeholders see a colourful educational landscape in Cuxhaven that offers good conditions for the successful training of skilled workers. One suggestion from the participants was to rely on tourism in marketing Cuxhaven as an attractive place to work. In addition, the participants would like to see the realisation of an initial pilot project to create an interface between industry and research.

Furthermore, a first workshop was held with interested stakeholders to analyse Cuxhaven as a knowledge-based location for maritime hydrogen applications and to develop measures for establishing a knowledge centre. The findings will be published in a separate third-party report.

2.3 Funding programmes for hydrogen projects

As part of the national hydrogen strategy and the European Green Deal, a large number of funding programmes are available throughout Germany and Europe. For example, the BMWi reports a funding volume of up to 1.4 billion EUR (Federal Ministry for Economic Affairs and Energy (BMWi) 2020). The EU funds hydrogen projects through the "Important Projects of Common European Interest" (IPCEI). These are transnational, important projects of common European interest. A total of 8 billion euros is to be invested in various projects. Additionally, the coalition agreement of the new German government stipulates the expansion of electrolysis capacity to around 10 GW in 2030. (Coalition agreement between SPD, Bündnis 90/Die Grünen and FDP 2021). OPEX costs are also to become eligible for funding in the EU in future. (European Commission 21.10.2021).

In addition to the existing subsidy programmes, there are many other funding programmes for the market ramp-up of hydrogen. This applies generally to all sectors. The following Table 10 lists examples of funding search engines.

Table 10: Selected funding search engines

Funding search engine	Link
Funding data base (Federal Government, Länder & EU)	https://www.foerderdatenbank.de/SiteGlobals/FDB/Forms/Suche/Expertensuche_Formular.html?submit=Suchen&filterCategories=FundingProgram
Funding initiative search PTJ	https://www.ptj.de/suche-foerderinitiativen
Funding & Tender opportunities (EU)	https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/home
TRIMIS Search Hub (EU)	https://trimis.ec.europa.eu/search?facets_query=&filter=&sort_by=search_api_relevance&sort_order=DESC&f%5B0%5D=type%3Aprogramme
Tender24	https://www.tender24.de/NetServer/PublicationSearchControllerServlet?function=SearchPublications&Gesetzesgrundlage=All&Category=InvitationToTender&thContext=publications

Table 12 in the appendix also lists regional, national and Europe-wide funding programmes that can be called upon directly. In the maritime sector, for example, the sustainable modernisation of coastal ships could be relevant for Cuxhaven. The BMDV published the fourth funding announcement at the beginning of December with a deadline for submitting applications by 28.02.2023. The BMWK also promotes the construction of refuelling vessels for LNG and sustainable renewable fuel alternatives in shipping.

3 Action plan for the city of Cuxhaven

3.1 SWOT analysis of the city of Cuxhaven and the region

In preliminary step for the action plan, a strengths, weaknesses, opportunities and threats (SWOT) analysis is carried out for the city of Cuxhaven based on the market analysis of the city of Cuxhaven and the surrounding area (Chapter 2).

Strengths

- Approx. 97 % (approx. 80 MW) large share of installed capacity for electricity generation from renewable energies with expansion to approx. 98 % (approx. 97 MW) through commissioning of a thermal power plant
- Natural deposits of salt and clay rock layers in the Cuxhaven region
- Good traffic connections via the A27 to Bremerhaven and Bremen as well as via the B73 to Stade and Hamburg
- Well-developed regional and supra-regional public transport system and connections to the rail network
- Strategically located deep water harbour with developed port infrastructure for roll-on roll-off cargo, container, offshore wind project cargo, heavy lift cargo, bulk cargo as well as general cargo shipments
- German Offshore Industry Centre (DOIZ) for the construction and shipping of all necessary components for offshore wind turbines
- Developed industrial site close to the port with an open area of 5.9 ha and further areas to be developed in the medium term
- Conversion of the Mittelplate supply fleet to hydrogen hybrid propulsion and construction of a landside hydrogen refuelling station for application in heavy-duty transport as part of the H2Move project with an option for expansion
- Strengthening the hydrogen value chain in the mobility sector across the Northwest through Hyways for Future (BMDV funding)
- Existing cooperation between important local educational institutions, such as the Elsfleth University of Applied Sciences, the Fraunhofer IFAM and the BBS Cuxhaven, to prevent shortage of qualified employees
- Several interested and partly already active actors in the hydrogen field

Weaknesses

- No connection to the extra-high voltage grid (current connection only 110 kV)
- No landing of an offshore power cable to convert larger amounts of wind power onshore into hydrogen and downstream products
- No connection of Cuxhaven to the hydrogen network of the "European Backbone" before 2050 according to the network development plan of the long-distance gas network operators
- No landing of natural gas transported by ship via floating or fixed terminals foreseen, which could later be converted to hydrogen
- Currently only a small existing local heating network in Cuxhaven (e.g., for the subsequent employment of waste heat from electrolysers).

Opportunities

- Operation of natural rock strata to build cavern storage facilities for large-volume hydrogen storage
- Conversion of public transport and additional rail connections to hydrogen operation
- Settlement of companies from the (offshore) hydrogen value chain on the vacant industrial area as well as companies for hydrogen processing into derivatives
- Existing hydrogen projects motivate other market participants to convert their logistics or production to hydrogen
- Medium-term hydrogen production from offshore wind in the (German) North Sea and landfall in Cuxhaven
- Green hydrogen imports by ship
- Establishment of a bunker station for green marine fuels and thus green shipping (Cuxhaven as a "green corridor")
- Further refinement of hydrogen into other hydrogen-based energy carriers, such as ammonia or methanol

Risks

- No landing of hydrogen by pipeline or imports
- Ocean shipping favours another port for bunkering hydrogen-based energy carriers

3.2 Action plan for the city of Cuxhaven and the region

Considering the results of the SWOT analysis, five action recommendations for the city of Cuxhaven and the region are now highlighted and initial measures are formulated.

1. Recommendation: Ensure political backing in the region

Explanation:

For the development of regional networks and a regional sustainable future concept of economy and society as well as its implementation, the support of local politics is an important criterion for success. The associated tasks and projects can be carried out and implemented more easily and efficiently if politics pursues the same goals and is "on board".

Local politics" in this sense includes:

- At the municipal level/county level: city council/city councillors/municipal council members, district administrator, members of the district council, mayor
- Various committees: Urban Planning, Economy, Tourism, Transport, Environment, etc.
- Administrative heads of the departments and offices involved

Basis for recommendation:

The amended Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz) came into force on January 1st, 2023. The targets provide for a limitation of global warming to 1.5 °C, a share of at least 80 % of renewable energies in gross electricity consumption by 2030 and a reduction of dependence on fossil energy sources. To achieve this, renewable energies are to be granted legal priority and the expansion paths for wind and solar energy must be significantly increased. Offshore wind energy, in particular, is supposed to be expanded to 30 GW by 2030 and to at least 70 GW by 2045. Furthermore, the federal government promotes innovative concepts for combining renewable energy generation and local hydrogen-based electricity storage. In this context, the expansion of offshore wind energy and local hydrogen production is a great opportunity for Cuxhaven, as this is where the region's strengths unfold, with a high proportion of renewable energies and the deep-water harbour as well as the DOIZ handling offshore wind project cargo. The state government of Lower Saxony is also committed to the "North German Hydrogen Strategy" and, together with the federal government, is currently providing 2.3 billion euros for hydrogen projects. The course for a future green hydrogen economy is laid out.

First measures:

- Establishing a common vision with local stakeholders and policy makers
- Allocating human resources, e.g., in the form of a site manager for hydrogen projects and stakeholder management
- Examining the possibility of policy incentive options for businesses in the region

2. Recommendation: Further consolidate and expand DOIZ and the port as a foundation

Explanation:

The DOIZ is considered an important component of Cuxhaven's harbour and the local value creation. Strengthening the location and expanding the infrastructure is the cornerstone for attracting more companies.

Basis for recommendation:

The establishment of a (green) hydrogen value chain includes not only the production, distribution, and utilization of hydrogen, but also component manufacturing in all areas spanning the hydrogen value chain. This starts with the production of components for the generation of green electricity, which can later be applied to produce hydrogen. Power generation applying offshore wind turbines displays enormous potential. Industrial centres that specialise in the production, handling, operation, and maintenance of such plants can therefore profit. This is especially true for locations that exhibit direct access to the sea, so that long transport routes over land are avoided.

The port of Cuxhaven and the associated DOIZ offer an optimal starting point with the existing infrastructure and company settlement in the offshore industry sector: as one of Germany's largest multi-purpose ports on the southern bank of the Elbe estuary, it represents a strategically favourable location for importing and exporting the required components. The deep water port reveal infrastructural advantages of a trimodal multi-purpose terminal for container and RoRo handling, among other things, with a connection to rail as well as road transport. Additional terminals are available for bulk cargo and general cargo as well as for the handling and storage of offshore wind project cargo and heavy lift cargo. Cuxhaven displays a well-developed port infrastructure with berths for ships with a pronounced draught. The announced support of 100 million euros from the Lower Saxony state government for port expansion illustrates the importance of the location. The expansion of the area offers local companies planning security for future projects and is a positive signal for (industrial) new settlements. By attracting more companies to this area, synergies can be created (e.g., short production routes) and joint resources can be developed (e.g., joint logistics infrastructure). For instance, an expansion in the diversity of companies towards manufacturers of electrolysers to couple with offshore wind power plants for green hydrogen offshore is conceivable.

Furthermore, in addition to the production of components for the development of a hydrogen economy, the DOIZ can establish itself as a future hydrogen consumer in logistics, so that production and logistics convert into climate neutral. Further industrial hydrogen consumers could settle in the eastern part of Cuxhaven near the harbour, with a currently vacant building site of approx. 5.9 ha.

First measures:

- Developing the infrastructure on site - development and connection of the properties
- Contacting local businesses to identify further needs:
  - Enquiry about plans for possible expansion of the production facilities, offer of individual workshop
  - Working out requirements for the infrastructure (wish list)
- Establishing a round table between electricity producers, grid operators and large-scale consumers or prospective hydrogen producers
- Continuing active advertising measures and approaching further supplier companies in the offshore sector
- Examining and creating policy incentives
- Strengthening the training of qualified employees on site and establishing a knowledge centre together with the Cuxhaven BBS, the Elsfleth University of Applied Sciences, the Fraunhofer IFAM and the Chamber of Industry and Commerce.

3. Recommendation: Mobility applications to foster the regional hydrogen economy in Cuxhaven

Explanation:

Decisive for the ramp-up of the hydrogen economy in Cuxhaven is not only the supply of hydrogen on site, but also securing its purchase. In particular, the public transport or mobility sector can provide initial planning security in this regard and simultaneously accomplish a significant contribution to reducing greenhouse gas emissions. This includes the conversion of public transport to hydrogen-powered vehicles, the employment of additional hydrogen trains on non-electrified sections of the route, and the supply of compressed hydrogen to the first ferries to promote water-side decarbonisation as well. To supply DOIZ onshore with materials, parts, and modules for production, an initial conversion of logistics to hydrogen-powered vehicles and CO_2-neutral logistics could develop.

Basis for recommendation:

Cuxhaven display many strengths that are of central importance for a future hydrogen economy. With currently 67 MW of installed wind and 11 MW of installed PV capacity, the region exhibits a good basis for producing hydrogen from surplus renewable electricity. The construction of a 2 MW electrolyser with an attached refuelling station for heavy-duty transport will ensure an initial market ramp-up. The construction of the hydrogen infrastructure provides an incentive to convert further segments of the mobility sector. If the market conditions are favourable, scaling up to 20 MW hydrogen generation capacity is envisaged in the medium term. At the same time, the conversion of the Mittelplate supply fleet to hydrogen hybrid propulsion creates another pilot project in the maritime sector, which could serve as a model to motivate other market participants towards converting their shipping fleet.

In the logistics sector, Niedersachsen Ports, for example, could establish itself as an industrial customer within the framework of the application of hydrogen-powered port equipment, such as mobile harbour cranes, gantry cranes, stacking cranes, reach stackers, forklifts or straddle carriers. At present, however, these technologies are not available, but are evaluated in the HHLA Clean Port & Logistics network.

First measure:

- Carrying out a hydrogen demand analysis or forecast in the mobility sector together with the individual stakeholders (land-based and maritime).
  - Status quo analysis: Analysis of the respective fleet size and travel distances to calculate consumption and mileage depending on the composition of the fleet (vehicle/ship types) and the route
  - Vehicle/vessel life and replacement cycles: Determining with stakeholders when and what proportion of new vehicles/vessels should be hydrogen-powered vehicles/vessels, examining conversion options in shipping
  - Hydrogen demand/quantity framework: Calculating the quantity structure depending on the ramp-up of hydrogen-powered vehicles/vessels
- Expanding hydrogen generation capacity with the extension of refuelling station infrastructure and converting fleets/introducing of hydrogen-powered ships/ferry services

4. Recommendation: Establish hydrogen processing industry and provide hydrogen-based synthesis products - especially as maritime fuel

Explanation:

In order to apply locally produced or sea landed hydrogen (on a large scale) in the shipping sector, a hydrogen processing industry is required to provide hydrogen-based fuels, such as ammonia or methanol. These could be applied in high seas shipping due to their higher energy density.

Basis for recommendation:

The synthesis of ammonia and methanol offers the possibility of further processing hydrogen and increasing the application options. In particular, fuels in the form of ammonia and methanol could be produced for ship propulsion systems. Additionally, maritime onward transport as freight might be an option.

On the water side, the location of Cuxhaven displays the advantage of proximity to the German Bight, the shipping lines of the Kiel Canal (NOK) and the Elbe fairway. This means that all ships manoeuvring from or towards the NOK or Hamburg pass through Cuxhaven. The favourable location of the harbour exhibits advantages regarding short cruises for a hydrogen, methanol or ammonia intake of ships at a bunkering station. Due to the deep draught, it is possible to refuel any class of ship.

The vacant development site directly in the vicinity of the port and the high proportion of renewable energies could be employed for the development of on-site hydrogen production in advance, with the possibility of synthesis, storage and refuelling also appear there. Should hydrogen be later landed by ship or pipeline, the existing synthesis capacities could be further expanded.

Furthermore, the waste heat generated during hydrogen production could be employed to supply local heating to neighbourhoods. The extent, to which the waste heat from the downstream exothermic ammonia synthesis can be applied, should be examined. There is currently only a small local heating network in Cuxhaven. In combination with the wood-fired power plant that is currently under construction this could lay a good foundation for expanding and securing the local heating network.

First measures:

- Identifying Stakeholders and analysing actors in the methanol/ammonia sector (both producers and purchasers)
- Contacting stakeholders and discussing the vision of a hydrogen and hydrogen processing industry in Cuxhaven
- Highlighting the initial needs of the actors
- Investigating the vacant spaces in terms of permitting legislation regarding the construction of an ammonia or methanol production facility

Note: The expansion of this industry is closely linked to Recommendation No. 5.

5. Recommendation: Erect large storage facilities for hydrogen or construct a bunker station for hydrogen and its synthesis products

Explanation:

Storage facilities are required for the intermediate storage of hydrogen for application in line with demand and decoupled from production or delivery. The operation of caverns is particularly suitable for large storage volumes. In this context, Cuxhaven and the surrounding area display several underground salt and clay rock layers that could provide large-volume storage facilities once they are explored. These would allow Cuxhaven to store hydrogen on a large scale and make it available as necessary.

The downstream synthesis to ammonia or methanol (see recommendation 4) and the subsequent bunkering of ships (fuel and/or cargo) shows great potential for Cuxhaven and it is recommended to establish a corresponding bunkering option (e.g., bunkering station).

Basis for recommendation:

The gas network development plan does not envisage an onshore pipeline connection from Cuxhaven to the German or European hydrogen network (European Hydrogen Backbone) until 2050 (FNB Gas 2022). However, Cuxhaven exhibits a favourable location close to the planned AquaDuctus offshore hydrogen pipeline in the German Bight and shows the geographical potential for a possible spur line connection. A connection to the energy island in the Elbe estuary, which is currently in the concept phase, would also be conceivable.

In order to provide the landed hydrogen quantities on a large scale according to demand or, if necessary, to process them further, there is a need for storage facilities. Here, the salt and clay rock layers running underground could be suitable for large-volume hydrogen storage with the construction of caverns. A direct large-volume, container-based onward transport by truck or rail depends heavily on the geographical location of the customers and may prove unprofitable compared to landing at other ports. A connection to the German hydrogen gas network in Bremen with the construction of an approx. 105 km long long-distance gas pipeline (cost estimate by gas network operator: EUR 158 million, as of December 2022) also appears unlikely at the current time in view of the aforementioned non-consideration in the network development planning. In principle, the gas network operators state themselves as open to adjustments in their planning should a large demand for hydrogen develop in Cuxhaven or a large landing of hydrogen be announced.

As described in Recommendation 3, there is great potential in the maritime utilization of hydrogen and land-based mobility applications. In particular, the bunkering of ships, e.g., for offshore operation (SOV (Service Operation Vessel), jack-up ships and smaller ships such as CTVs (Crew Transfer Vessel) can be a significant growth market. Deep-see vessels could be fuelled with hydrogen-based derivatives such as ammonia or methanol. Different bunkering strategies can be considered for this, as explained below in the context of the first measures.

First measures:

- Assessing the subareas TG006, TG075, TG067 and TG068 from the report of the Öko-Institut as prospective cavern storage facilities for hydrogen
- Establishing or maintaining contact with stakeholders of the offshore hydrogen pipeline for consideration of a spur line.
  - Aspects to be considered for the implementation of such a spur line are the highly frequented shipping line of the Elbe to be crossed and its dredging depth as well as various protected areas such as the Schleswig-Holstein Wadden Sea and a large number of nearby protected areas (bird sanctuaries, particularly sensitive sea area (PSSA), protection zone 1). The approval process for the construction of a spur line could therefore prove onerous
  - The hydrogen pipeline could be landed south-east of the harbour. This would require a licensing review for a suitable location.

- Planning of the bunker station
  - The method of refuelling depends on which energy carriers will be applied as fuels in future ship propulsion systems (e.g., GH_2, LH_2, ammonia, LOHC or methanol). Initial pilot projects analyse the refuelling of ammonia and methanol. For example, a bunker barge for the fuel ammonia is planned during the hydrogen flagship project "TransHyDE-Campfire" funded by the Federal Ministry of Education and Research. Methanol is already an established fuel in shipping - common bunker barges can be reused for this.
  - There are several options for implementing hydrogen or derivative bunkering of ships, each with different advantages and disadvantages:
    - A common option for bunkering is the water-side fuel transfer from a bunker barge to the receiving ship (STS: Ship-to-Ship). In this case, the bunker barge is moored alongside the receiving ship to realise the hydrogen transfer. Cargo ships are bunkered in this way to save time during scheduled cargo handling at the port of loading or discharge. The advantage of this method is that bunkering can occur at the same time as cargo handling and it does not interfere with port operations.
    - A shore-based bunkering option that is largely flexible is trailer-based bunkering (TTS: Truck-to-Ship). Fuel-loaded trailers are positioned at the quay edge and connected to the ship by means of bunker hoses. Depending on the ship, it is possible to connect several trailers to the ship's tanks at the same time and thus achieve a higher transfer rate. The advantage of this method is that trailers can usually also be placed in fishing ports and marinas and can thus refuel smaller ships, boats and yachts. Furthermore, this method allows cargo handling at the same time.
    - The transfer of hydrogen in exchangeable tank containers is another flexible option in terms of location. Here, empty mobile tank containers are unloaded from the ships and replaced by full ones. This is only feasible if the ship is designed for this.
    - With a permanently installed hydrogen bunkering station (PTS: Port-to-Ship), ships are bunkered at a special berth. Depending on the design, a bunker station can be applied for various ships. For time reasons, it is usually not possible for cargo ships to stop at a bunker station for a bunkering process lasting several hours, as cargo handling is not possible at this point. Here it would be conceivable to merely bunker a bunker barge at the bunker station in order to subsequently transfer the renewable energy carrier to the cargo ship at the location of the cargo transfer.

List of figures

List of tables

Bibliography

Academic (2022): Bahnstrecke Hamburg–Cuxhaven. Online verfügbar unter https://de-academic.com/dic.nsf/dewiki/132406, zuletzt aktualisiert am 30.04.2015, zuletzt geprüft am 01.12.2022.

Albrecht, Uwe; Ulrich Bünger; Michalski, Jan; Raksha, Tetyana; Wurster, Reinhold; Zerhusen, Jan (2020): Internationale Wasserstoffstrategien. Executive Summary. Hg. v. Weltenergierat – Deutschland e.V. Ludwig-Bölkow-Systemtechnik GmbH. Online verfügbar unter https://www.weltenergierat.de/wp-content/uploads/2021/03/WEC_H2_Strategie_Executive-Summary_DE_final.pdf, zuletzt geprüft am 06.01.2022.

Alstom (2022): Weltpremiere: Erstes Netz mit 14 Wasserstoffzügen nimmt in Niedersachsen Betrieb mit Passagieren auf. Online verfügbar unter https://www.alstom.com/de/press-releases-news/2022/8/weltpremiere-erstes-netz-mit-14-wasserstoffzuegen-nimmt-niedersachsen, zuletzt geprüft am 14.11.2022.

Andreas Gelfort; Christian Schneller; Philipp Heuser; Leona Jovy; Philipp Steffens; Vito Tisci (2022): H2-Barometer. Unabhängige Bewertung der Wasserstoffwirtschaft in Deutschland. Hg. v. E-Bridge Consulting GmbH. Online verfügbar unter https://www.e-bridge.de/wp-content/uploads/2022/09/E-Bridge_H2-Barometer_Ausgabe-2_2022.pdf, zuletzt geprüft am 30.11.2022.

AquaVentus (2022): AquaVentus-Vision. Online verfügbar unter https://aquaventus.org/, zuletzt geprüft am 14.11.2022.

Bloomberg NEF (2022): 2H 2022 Hydrogen Market Outlook – Policy Finally Arrives. Blomberg Finance.

BMDV (2022a): Die Beförderung gefährlicher Güter. Online verfügbar unter https://www.bmdv.bund.de/SharedDocs/DE/Publikationen/G/die-befoerderung-gefaehrlicher-gueter.pdf?__blob=publicationFile, zuletzt geprüft am 24.11.2022.

BMDV (2022b): Gefahrgut - Recht / Vorschriften - Straße. Online verfügbar unter https://bmdv.bund.de/SharedDocs/DE/Artikel/G/Gefahrgut/gefahrgut-recht-vorschriften-strasse.html, zuletzt aktualisiert am 14.12.2022, zuletzt geprüft am 14.12.2022.

BMWi (2018): Erneuerbare Energien in Zahlen. Nationale und internationale Entwicklungen im Jahr 2018, 21 ff. Online verfügbar unter https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/erneuerbare-energien-in-zahlen-2018.pdf?__blob=publicationFile&v=24, zuletzt geprüft am 14.01.2022.

Bründlinger, Thomas; Elizalde König, Julian; Frank, Oliver; Gründig, Dietmar; Jugel, Christoph; Kraft, Patrizia et al. (2018): dena-Leitstudie - Integrierte Energiewende. Impulse für die Gestaltung des Energiesystems bis 2050. Teil A: Ergebnisbericht und Handlungsempfehlungen (dena) ; Teil B: Gutachterbericht (ewi Energy Research & Scenarios gGmbH). Hg. v. Deutsche Energie-Agentur GmbH (dena).

BUND (2016): Stromeinsatz zu Heizzwecken. Online verfügbar unter https://www.bund.net/fileadmin/user_upload_bund/publikationen/bund/standpunkt/stromeinsatz_zu_heizzwecken_standpunkt.pdf, zuletzt geprüft am 14.01.2022.

Bundesministerium für Wirtschaft und Energie (BMWi) (2020): Die Nationale Wasserstoffstrategie. Online verfügbar unter https://www.bmwi.de/Redaktion/DE/Publikationen/Energie/die-nationale-wasserstoffstrategie.pdf?__blob=publicationFile&v=20, zuletzt geprüft am 07.01.2022.

C.A.R.M.E.N. e.V (2021): Marktübersicht Elektrolyseure. Online verfügbar unter https://www.carmen-ev.de/wp-content/uploads/2021/11/Marktuebersicht-Elektrolyseure_2021-11.pdf.

Clean Shipping Coalition (2021): UN SHIPPING AGENCY CLIMATE TALKS AGAIN HELD BACK BY HANDFUL OF BLOCKERS. Online verfügbar unter http://www.cleanshipping.org/news/un-shipping-agency-climate-talks-again-held-back-by-handful-of-blockers/, zuletzt geprüft am 21.12.2022.

Deutsches Offshore-Industrie Zentrum Cuxhaven (2022): HyExpert. Online verfügbar unter https://www.offshore-basis.de/wasserstoff/hyexpert/, zuletzt geprüft am 14.11.2022.

Dirk Altwig; Jörn Bischoff; Andrea Stein; Andrea Pujari (2022): Weltpremiere: Erstes Netz mit 14 Wasserstoffzügen nimmt in Niedersachsen Betrieb mit Passagieren auf. Hannover/Bremervörde. Online verfügbar unter https://www.lnvg.de/fileadmin/media/lnvg/Pressemitteilungen/20220824_Weltpremiere.pdf.

DNV (2021): Alternative Fuels for Containerships. Online verfügbar unter https://www.dnv.com/maritime/publications/alternative-fuels-for-containerships-download.html, zuletzt geprüft am 29.03.2022.

DNV (2022): Energy Transition Outlook. A global and regional forecast to 2050.

DOIZ (2022): Das Deutsche Offshore-Industrie-Zentrum Cuxhaven. Online verfügbar unter https://www.offshore-basis.de/, zuletzt aktualisiert am 14.12.2022, zuletzt geprüft am 14.12.2022.

DVGW (2022): DVGW energie | wasser-praxis konkret. Online verfügbar unter https://wvgw.de/dyn_pdf/ewp/2022/konkret/38/, zuletzt aktualisiert am 10.10.2022, zuletzt geprüft am 19.10.2022.

DVZ (2022): Methanol lohnt sich wirtschaftlich nicht. Online verfügbar unter https://www.dvz.de/rubriken/test-technik/alternative-antriebe/detail/news/methanol-lohnt-sich-wirtschaftlich-nicht.html, zuletzt geprüft am 21.12.2022.

E.W.E. AG (2022): Planausschnitt Cuxhaven Stadt.

Esfeh, Shaghayegh Kazemi; Monnerie, Nathalie; Mascher, Sophia; Baumstark, David; Kriechbaumer, Dorottya; Neumann, Nicole et al. (2022): Zukünftige maritime Treibstoffe und deren mögliche Importkonzepte. Hg. v. Deutsches Zentrum für Luft- und Raumfahrt e. V. (DLR). Online verfügbar unter https://www.dlr.de/content/de/downloads/publikationen/broschueren/2022/kurzstudie-maritime-treibstoffe.pdf?__blob=publicationFile&v=4, zuletzt geprüft am 14.06.2022.

Europäische Kommission (21.10.2021): Staatliche Beihilfen: Kommission billigt neue Leitlinien für staatliche Klima-, Umweltschutz- und Energiebeihilfen. Maria TSONI, Arianna PODESTA. Online verfügbar unter https://ec.europa.eu/commission/presscorner/detail/de/ip_21_6982.

Europäische Kommission (2022): Delivering the European Green Deal. Online verfügbar unter https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_de, zuletzt geprüft am 21.12.2022.

European Parliament & Council (2019): Clean Vehicle Directive. Online verfügbar unter https://eur-lex.europa.eu/eli/dir/2019/1161/oj.

EWE (2022): Hyways for Future. Online verfügbar unter https://www.hyways-for-future.de/de/projekt, zuletzt geprüft am 14.11.2022.

Flughafen-Betriebsgesellschaft Cuxhaven/ Nordholz mbH: SeaAirport Cuxhaven/Nordholz. Take off for flexibility. Online verfügbar unter https://www.afw-cuxhaven.de/assets/Uploads/Broschuere_SeaAirport_Cuxhaven_Nordholz.pdf, zuletzt geprüft am 16.12.2022.

FNB Gas (2022): Wasserstoffbericht.

Fraunhofer (2019): Eine Wasserstoff-Roadmap für Deutschland. Online verfügbar unter https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/2019-10_Fraunhofer_Wasserstoff-Roadmap_fuer_Deutschland.pdf.

Frithjof Staiß; Jörg Adolf; Florian Ausfelder; Christoph Erdmann; Manfred Fischedick; Christopher Hebling et al. (2022): Optionen für den Import grünen Wasserstoffs nach Deutschland bis zum Jahr 2030. Transportwege – Länderbewertungen – Realisierungserfordernisse. Unter Mitarbeit von Nationale Akademie der Wissenschaften Leopoldina und Union der deutschen Akademien der Wissenschaften e. V. München (Schriftenreihe Energiesysteme der Zukunft). Online verfügbar unter https://energiesysteme-zukunft.de/fileadmin/user_upload/Publikationen/PDFs/Analyse_Wasserstoff_neu.pdf, zuletzt geprüft am 30.11.2022.

Gao, K.; Tengler, M.; Bhashyam, A.; Wang, X.; Bravante, M.; Annex, M. (2022): 1H 2022 Hydrogen Levelized Cost Update – Higher LCOE and Gas Prices. Hg. v. BloombergNEF.

GASCADE Gastransport: AquaDuctus (2022). Online verfügbar unter https://www.gascade.de/wasserstoff/aquaductus, zuletzt aktualisiert am 30.11.2022, zuletzt geprüft am 30.11.2022.

Getting to Zero Coalition (2021): The Next Wave Green Corridors. Online verfügbar unter https://www.globalmaritimeforum.org/content/2021/11/The-Next-Wave-Green-Corridors.pdf, zuletzt geprüft am 24.06.2022.

H2 Mobility (2022): H2-Tankstellennetz. Online verfügbar unter https://h2-mobility.de/en/, zuletzt geprüft am 19.10.2022.

Hanseatic Transport Consultancy und MKO Marine Consulting (2022): Mobile Landstromversorgung – Technologische Möglichkeiten und Voraussetzungen im Auftrag der NOW GmbH. Online verfügbar unter https://www.now-gmbh.de/wp-content/uploads/2022/09/NOW_Studie-Mobile-Landstromversorgung.pdf.

HHLA (2022): Startschuss für Innovationscluster: Wasserstoff soll schwere Hafentechnik antreiben. Online verfügbar unter https://hhla.de/medien/news/detailansicht/startschuss-fuer-innovationscluster-wasserstoff-soll-schwere-hafentechnik-antreiben, zuletzt geprüft am 12.12.2022.

Hickner, Michael A.; Herring, Andrew M.; Coughlin, E. Bryan (2013): Anion exchange membranes: Current status and moving forward. In: *J. Polym. Sci. Part B: Polym. Phys.* 51 (24), S. 1727–1735. DOI: 10.1002/polb.23395.

Holzheizkraftwerke Cuxhaven (2023): Der Strom aus Cuxhaven. Online verfügbar unter https://www.holz-heizkraftwerke.de/, zuletzt geprüft am 10.01.2023.

Hydrogentle GmbH (2019): Konzept zur Nutzung von Wasserstoff in Cuxhaven und im Elbe-Weser-Raum.

ifh Göttingen (2022): Wasserstoff-Infrastruktur und maritime Wirtschaft Technische, institutionelle und regionale Grundlagen für die Mittelstandspolitik. Online verfügbar unter https://ifh.wiwi.uni-goettingen.de/site/assets/files/6733/ifh_fb-3_2022.pdf.

IHK Lüneburg Wolfsburg (2022): H2Skills. Online verfügbar unter https://www.ihk.de/ihklw/produkte/beratung-und-service/energie-und-umwelt/h2skills-weiterbildungsbedarfe-im-wasserstoffsektor-5346640, zuletzt geprüft am 14.11.2022.

Ile-Region Moorexpress-Stader Geest (2020): 16. Sitzung der Lenkungsgruppe. Umsetzung der Fortschreibung des Regionalen Entwicklungskonzeptes 2014-2020.

International Energy Agency (2019): The Future of Hydrogen. Seizing today's opportunities. Report prepared by the IEA. Online verfügbar unter https://iea.blob.core.windows.net/assets/9e3a3493-b9a6-4b7d-b499-7ca48e357561/The_Future_of_Hydrogen.pdf, zuletzt geprüft am 08.01.2022.

International Renewable Energy Agency (IRENA) (2021): Green Hydrogen Supply: A Guide to Policy Making. A Guide to Policy Making. Website. Online verfügbar unter https://www.irena.org/publications/2021/May/Green-Hydrogen-Supply-A-Guide-To-Policy-Making, zuletzt aktualisiert am 01.10.2022, zuletzt geprüft am 01.10.2022.

IRENA (2020): Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5C climate goal. Online verfügbar unter https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf.

IRENA (2021): Making the breakthrough: Green hydrogen policies and technology costs. Online verfügbar unter https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_Hydrogen_breakthrough_2021.pdf?la=en&hash=40FA5B8AD7AB1666EECBDE30EF458C45EE5A0AA6#:~:text=The%20electrolyser%20investment%20cost%20for,Based%20on%20IRENA%20analysis.

Koalitionsvertrag zwischen SPD, Bündnis 90/Die Grünen und FDP (2021). Online verfügbar unter https://www.bundesregierung.de/resource/blob/974430/1990812/04221173eef9a6720059cc353d759a2b/2021-12-10-koav2021-data.pdf?download=1, zuletzt geprüft am 14.01.2022.

KONGSTEIN (2021): OffsH2ore. Online verfügbar unter https://kongstein.com/offsh2ore-a-concept-design-study-for-offshore-hydrogen-production-from-offshore-wind-in-island-mode-configuration/.

KVG Stade GmbH & Co KG (2021a): Zahlenspiegel. Online verfügbar unter https://www.kvg-bus.de/fileadmin/user/pdf/zahlenspiegel_2021.pdf, zuletzt geprüft am 16.01.2023.

KVG Stade GmbH & Co. KG (2021b): Stadtliniennetz Cuxhaven. Online verfügbar unter https://www.kvg-bus.de/fileadmin/user/pdf/stadtliniennetz_cuxhaven_08.11.2021.pdf, zuletzt geprüft am 14.12.2022.

MAN (2022): Containerschiff reduziert Treibhausgas- Emissionen durch Betrieb mit synthetischem Kraftstoff. Online verfügbar unter https://www.man-es.com/de/home/2022/04/06/containerschiff-reduziert-treibhausgas--emissionen-durch-betrieb-mit-synthetischem-kraftstoff., zuletzt geprüft am 21.12.2022.

Manfred Klell; Helmut Eichlseder; Alexander Trattner (2018): Wasserstoff in der Fahrzeugtechnik: Erzeugung, Speicherung, Anwendung,. 4. Auflage.

McKinsey & Company (2022): Global Energy Perspective 2022. Executive Summary. Online verfügbar unter https://www.mckinsey.com/~/media/McKinsey/Industries/Oil%20and%20Gas/Our%20Insights/Global%20Energy%20Perspective%202022/Global-Energy-Perspective-2022-Executive-Summary.pdf, zuletzt geprüft am 21.07.2022.

Meinen, Heinke (2022): DLR - Institut für vernetzte Energiesysteme - Forschungsprojekt HyCavMobil. Online verfügbar unter https://www.dlr.de/ve/desktopdefault.aspx/tabid-13776/23923_read-57990/, zuletzt aktualisiert am 19.10.2022, zuletzt geprüft am 19.10.2022.

NDR (2023): Land gibt 100 Millionen für Hafenausbau in Cuxhaven. Online verfügbar unter https://www.ndr.de/nachrichten/niedersachsen/oldenburg_ostfriesland/Land-gibt-100-Millionen-fuer-Hafenausbau-in-Cuxhaven,aktuelloldenburg11512.html, zuletzt geprüft am 16.01.2023.

Niedersachsen Ports (2019): NPorts Perspektivpapier Nordseehafen Cuxhaven.

Niedersachsen Ports (2021): Port Information Guide Cuxhaven.

Niedersächsisches Ministerium für Umwelt, Energie, Bauen und Klimaschutz (2020): Energiewendebericht 2020.

Now GmbH (2018a): Studie IndWEDe Industrialisierung der Wasserelektrolyse in Deutschland Chancen und Herausforderungen für nachhaltigen Wasserstoff für Verkehr, Strom und Wärme. Online verfügbar unter https://www.dwv-info.de/wp-content/uploads/2019/06/NOW-Elektrolysestudie-2018.pdf.

Now GmbH (2018b): Rechtliche Rahmenbedingungen für ein integriertes Energiekonzept 2050 und die Einbindung von EE-Kraftstoffen. Berlin, zuletzt geprüft am 19.10.2022.

offshore-basis.de (2022a): Freie Industrie- und Gewerbeflächen. Online verfügbar unter https://www.offshore-basis.de/infrastruktur/freie-gewerbefl%C3%A4chen/, zuletzt aktualisiert am 30.11.2022, zuletzt geprüft am 30.11.2022.

offshore-basis.de (2022b): Terminals und Liegeplätze. Online verfügbar unter https://www.offshore-basis.de/infrastruktur/terminals-und-liegepl%C3%A4tze/, zuletzt aktualisiert am 29.11.2022, zuletzt geprüft am 29.11.2022.

Open Infrastructure Map (2022). Online verfügbar unter https://openinframap.org/, zuletzt aktualisiert am 13.11.2022, zuletzt geprüft am 16.01.2023.

Open Street Map (2022): Open Street Map. Hg. v. Google Maps.

Peter Kurzweil; Otto K. Dietlmeier (2018): Elektrochemische Speicher. Superkondensatoren, Batterien, Elektrolyse-Wasserstoff, Rechtliche Rahmenbedingungen: Springer Fachmedien Wiesbaden.

Philipp Gerbert; Patrick Herhold; Jens Burchardt; Stefan Schönberger (2018): Klimapfade für Deutschland. Hg. v. The Boston Consulting Group GmbH und Prognos AG. Online verfügbar unter https://www.prognos.com/sites/default/files/2021-01/20180118_bdi_studie_klimapfade_fuer_deutschland_01.pdf, zuletzt geprüft am 19.10.2022.

Sachverständigenrat für Umweltfragen (2021): Wasserstoff im Klimaschutz: Klasse statt Masse. Stellungnahme | Juni 2021. Online verfügbar unter https://www.umweltrat.de/SharedDocs/Downloads/DE/04_Stellungnahmen/2020_2024/2021_06_stellungnahme_wasserstoff_im_klimaschutz.pdf?__blob=publicationFile&v=4.

Saleem Chaudry, Judith Krohn (2022): Fachliche Beratung des Landkreises Cuxhaven zu den Ergebnissen des Zwischenberichts Teilgebiete im Standortauswahlverfahren für ein Endlager. In: *Öko-Institut e.V.*

SPD, BÜNDNIS 90/DIE GRÜNEN, FDP (2021): Koalitionsvertrag. Bündins für Freiheit, Gerechtigkeit und Nachhaltigkeit. Mehr Fortschritt Wagen. Hg. v. SPD, BÜNDNIS 90/DIE GRÜNEN, FDP.

Staiß, Frithjof; Adolf, Jörg; Ausfelder, Florian; Erdmann, Christoph; Hebling, Christopher; Jordan, Thomas et al. (2022): Optionen für den Import grünen Wasserstoffs nach Deutschland bis zum Jahr 2030. Unter Mitarbeit von Nationale Akademie der Wissenschaften Leopoldina und Union der deutschen Akademien der Wissenschaften e. V. Online verfügbar unter https://energiesysteme-zukunft.de/fileadmin/user_upload/Publikationen/PDFs/Analyse_Wasserstoff_neu.pdf, zuletzt geprüft am 18.10.2022.

Stecherle, Philip; Brandes, Julian; Heilig, Judith; Wrede, Daniel; Kost, Christoph; Schlegl, Thomas et al. (2020): Wege zu einem klimaneutralen Energiesystem. Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen. Hg. v. Fraunhofer Institute for Solar Energy Systems (ISE). Freiburg.

Sterner, M. (2017): Notwendigkeit und Chancen für Power-to-X-Technologien. Online verfügbar unter https://www.uniper.energy/storage/sites/default/files/2017-12/2017_okt_energiewirtschaftliches_kurzgutachten_fur_ptx-allianz.pdf, zuletzt geprüft am 14.01.2022.

Tagesspiegel (2022): EU einigt sich auf maritimen Emissionshandel. Online verfügbar unter https://background.tagesspiegel.de/energie-klima/eu-einigt-sich-auf-maritimen-emissionshandel, zuletzt geprüft am 21.12.2022.

Teuffer (2022): Roadmap für Wasserstoffspeicher veröffentlicht. In: *energate GmbH*, 06.12.2022. Online verfügbar unter https://www.energate-messenger.de/news/228662/roadmap-fuer-wasserstoffspeicher-veroeffentlicht, zuletzt geprüft am 10.01.2023.

Umweltbundesamt (2022): Seeschifffahrt. Online verfügbar unter https://www.umweltbundesamt.de/themen/wasser/gewaesser/meere/nutzung-belastungen/schifffahrt#fakten-zur-seeschifffahrt-und-zu-ihren-auswirkungen-auf-die-umwelt, zuletzt geprüft am 21.12.2022.

UN Climate Change Conference UK (2021): CLYDEBANK DECLARATION FOR GREEN SHIPPING CORRIDORS. Online verfügbar unter https://ukcop26.org/cop-26-clydebank-declaration-for-green-shipping-corridors/, zuletzt geprüft am 21.12.2022.

van Rossum, Rik; Jens, Jaro; La Guardia, Gemma; Wang, Anthony; Kühnen, Luis; Overgaa, Martijn (2022): European Hydrogen Backbone. Online verfügbar unter https://gasforclimate2050.eu/wp-content/uploads/2022/04/EHB-A-European-hydrogen-infrastructure-vision-covering-28-countries.pdf.

Vito Milella; Bodo Nachbar; Andrew Kelly; Stefan Lieske; Stephan Bude; Thomas Bayer et al. (2020): Potenzialbeschreibung Potenzialbeschreibung - Wasserstofftransport über das Schienennetz. Unter Mitarbeit von Mistill Kilicarslan. Hg. v. DB Energie GmbH. Online verfügbar unter https://blog.lea-hessen.de/wp-content/uploads/2020/08/Potenzialbeschreibung-Wasserstofftransport-%C3%BCber-das-Schienennetz.pdf, zuletzt geprüft am 18.10.2022.

Warnecke, Matthias; Röhling, Simone (2021): Underground hydrogen storage – Status quo. In: *zdgg* 172 (4), S. 641–659. DOI: 10.1127/zdgg/2021/0295.

Wasserstraßen- und Schifffahrtsverwaltung des Bundes (2023): Wasserstraßen- und Schifffahrtsverwaltung des Bundes. Online verfügbar unter https://www.wsa-elbe-nordsee.wsv.de/Webs/WSA/Elbe-Nordsee/DE/1_Wasserstrassen/1_Revier/Elbe/elbe_node.html, zuletzt geprüft am 27.01.2023.

Wintershall DEA (2022): Wasserstoffprojekt H2Move nimmt in Cuxhaven Fahrt auf. Online verfügbar unter https://wintershalldea.de/de/newsroom/clone-wasserstoffprojekt-h2move-nimmt-cuxhaven-fahrt-auf, zuletzt geprüft am 14.11.2022.

Wuppertal Institut; DIW Econ: Bewertung der Vor- und Nachteile von Wasserstoffimporten im Vergleich zur heimischen Erzeugung. Online verfügbar unter https://wupperinst.org/fa/redaktion/downloads/projects/LEE-H2-Studie.pdf, zuletzt geprüft am 30.11.2022.

Zentralverband der deutschen Seehafenbetriebe e. V. (2021): Seehäfen in der Energiewende: Wasserstoff. Arbeitspapier.

Appendix

Table 11: Market overview electrolysers, according to (C.A.R.M.E.N. e.V 2021) (IRENA 2021)

Provider	Tech-nology	Model	H_2 Quantity (Nm^3 /h)	Power class
AquaHydrex (USA)	AEL	k. A.	k. A.	k. A.
AREVAH2 (FR)	PEM	k. A.	k. A.	k. A.
AsahiKASEI (JPN)	AEL	Electrolyzer Acilyzer™	k. A.	k. A.
AVX/Kumatec Hydrogen (EN)	PEM	PEM-40-100 PEM-100-25 PEM-40-1000	20 5 200	100 kW 3 kW 1000 kW
Carbotech (DE)	PEM	k. A.	k. A.	k. A.
Ceres (GBR)	HTEL	k. A.	k. A.	k. A.
Cockerill Jingli (CHN)	AEL	k. A.	k. A.	k. A.
Bloomenergy (USA)	HTEL	Bloom Electrolyzer	86,8	360 kW
Denora (IT)	PEM AEL	k. A.	k. A.	k. A.
Elogenies (FR)	PEM	E Series (5 models)	10 - 1000	50- 5000 kW
Enapter (EN)	AEM	EL 2.1 AEM Multicore	5 208,3	1 MW
Giner ELX (USA)	PEM	k. A.	k. A.	k. A.
Green Hydrogen Systems (DNK)	AEL	HyProvide A Series (3 models)	30/60/90	1 MW
Haldor Topsoe (DNK)	HTEL	k. A.	k. A.	k. A.
HIAT (EN)	PEM	HYP40 HYP100	20 5	102 kW 35 kW
Hitachi Zosen (JPN)	AEL/PEM	k. A.	k. A.	k. A.
Höller Electrolyzer (DE)	PEM	Prometheus (3 models)	k. A.	k. A.
Honda (JPN)	PEM	k. A.	k. A.	k. A.
H-Tec Systems (DE)	PEM	ME 100/350 ME 450/1400	47 210	225 kW 1000 kW
Hydrogen Pro (NOR)	AEL	k. A.	k. A.	k. A.
Hydrogenics (USA)	PEM AEL	HyLyzer (5 models) HySTAT (6 models)	199,5 - 1000 9,7 - 99,5	k. A.
Hygear (NL)	AEL	Hy.Gen-e (5 models)	10 - 250	k. A.
iGas (DE)	PEM	k. A.	k. A.	k. A.
ITM Power (GBR)	PEM	HGAS (5 models)	122,2 - 1875	707-5000 kW
Kobelco (JPN)	AEL/PEM	k. A.	k. A.	k. A.
McPhy Energy (FR)	AEL	Piel (4 models) Mclyzer (6 models)	0,4 - 10 10 - 800	3 - 60 kW 50 - 100 kW
NEL (NOR)	PEM AEL	M Series / S series / H Series / C Series A Series	4,920 3,880	k. A.
NextHydrogen (CAN)	AEM	NH 100 / 300 / 500	17 - 500	k. A.
OxEon Energy (USA)	HTEL	Prototype	k. A.	k. A.
Peric (CHN)	AEM PEM	KCDQ (13 models) SDQ (10 models)	k. A. k. A.	k. A.
PlugPower (USA)	PEM	1 MW Electrolyzer 5 MW Electrolyzer ALLGASH (2 models) MERRIMACK (2 models)	200 1000 50 - 200 10 - 30	k. A.
Shanghai Zhizhen (CHN)	AEL	k. A.	k. A.	k. A.
Siemens energy (DE)	PEM	Silyzer 300	1100,1 - 22222,2	k. A.
Solidpower (IT)	HTEL	k. A.	k. A.	k. A.
Sunfire (EN)	HTEL	Sunfire HyLink SOEC	750	k. A.

	AEL	Sunfire HyLink Alkaline	2230	
Sylvester (FR)	HTEL	Prototype	k. A.	k. A.
Teledyne (USA)	PEM	k. A.	k. A.	k. A.
Thyssenkrupp (DE)	AEL	20 MW modules	4000	k. A.
Tianjin (CHN)	AEL	k. A.	k. A.	k. A.
Toshiba (JPN)	HTEL	k. A.	k. A.	k. A.

Table 12: Overview of funding programmes

Exemplary funding programmes	**Funding body**	**Link**
Regional		
Hydrogen Economy Pilot and Demonstration Projects (Hydrogen Directive)	Nds. Ministry for the Environment, Energy, Building and Climate Protection	https://www.foerderdatenbank.de/FDB/Content/DE/Foerderprogramm/Land/Niedersachsen/wasserstoffrichtlinie.html#:~:text=The%20Land%20of%20Lower% Saxony%20supports%C3%BCt%20you,F%C3%B6rderung%20f%C3%BCr%20Individual%2D%20or%20Composite%20Projects.
Investment support for individual enterprises	Nbank	https://www.nbank.de/F%C3%B6rderprogramme/Aktuelle-F%C3%B6rderprogramme/Einzelbetriebliche-Investitionsf%C3%B6rderung.html#aufeinenblick
Innovation Promotion Programme for Research and Development in Enterprises (IFP)	Nbank	https://www.nbank.de/F%C3%B6rderprogramme/Aktuelle-F%C3%B6rderprogramme/Innovationsf%C3%B6rderprogramm-f%C3%BCr-Forschung-und-Entwicklung-in-Unternehmen-(IFP).html#at-a-glance
Improving urban/rural mobility in local public transport (flexible forms of service)	Nbank	https://www.nbank.de/F%C3%B6rderprogramme/Aktuelle-F%C3%B6rderprogramme/Verbesserung-der-Stadt-Umlandmobilit%C3%A4t-im-%C3%B6ffentlichen-Personennahverkehr-(flexible-operation-forms).html#hvvcalculation-tool
Acquisition of fuel cell-powered municipal special vehicles	Nds. Ministry for the Environment, Energy, Building and Climate Protection	https://www.nbank.de/F%C3%B6rderprogramme/Aktuelle-F%C3%B6rderprogramme/Anschaffung-brennstoffzellenbetriebener-kommunaler-Spezialfahrzeuge.html#aufeinenblick
Germany-wide		
Electrochemical Materials and Processes for Green Hydrogen and Green Chemistry (ECCM)	BMWK, BMBF	https://www.ptj.de/en/project-funding/applied-energy-research/eccm
Call for German-Chinese R&D cooperation projects in the field of hydrogen and fuel cell vehicles	BMDV	https://www.now-gmbh.de/foerderung/foerderfinder/deutsch-chinesische-forschungs-und-entwicklungs-kooperationsprojekte/
Promotion of light and heavy commercial vehicles with alternative, climate-friendly drive systems and associated refuelling and charging infrastructure for electrically powered commercial vehicles	BMDV	https://www.bag.bund.de/DE/Foerderprogramme/KlimaschutzundMobilitaet/KSNI/Ksni_node.html
National Hydrogen and Fuel Cell Technology Innovation Programme (NIP II): R&D projects on hydrogen and fuel cells	BMDV	https://www.now-gmbh.de/wp-content/uploads/2021/09/NIP-II-Foerderrichtlinie-FEI-2021.pdf

Exemplary funding programmes	**Funding body**	**Link**
National Hydrogen and Fuel Cell Technology Innovation Programme Phase II (NIP) - Market Activation Measures - Focus on Sustainable Mobility	BMDV	https://www.ptj.de/nip
Sustainable modernisation of coastal vessels	BMDV	https://www.namkue.de/
Development of renewable fuels	BMDV	https://www.now-gmbh.de/foerderung/foerderprogramme/regenerative-kraftstoffe/
KMU-innovativ: Resource efficiency and climate protection	BMBF	https://www.bmbf.de/bmbf/de/forschung/innovativer-mittelstand/kmu-innovativ/kmu-innovativ-ressourceneffizienz-und-klimaschutz/kmu-innovativ-ressourceneffizienz-und-klimaschutz.html
7th Energy Research Programme	BMBF	https://www.bmbf.de/bmbf/shareddocs/bekanntmachungen/de/2019/02/2337_bekanntmachung
Energy research programme - Research and development in the basic area	BMBF	https://www.ptj.de/projektfoerderung/anwendungsorientierte-grundlagenforschung-energie/ideenwettbewerb-gruener-wasserstoff
International projects on the topic of green hydrogen	BMBF	https://www.bmbf.de/bmbf/de/home/_documents/internationale-kooperationen-gruener-wasserstoff.html
Climate-neutral products through biotechnology - CO_2 and C_1 compounds as sustainable raw materials for the industrial bioeconomy (CO2BioTech)	BMBF	https://www.ptj.de/projektfoerderung/biooekonomie/co2biotech
KMU-innovativ: Materials research	ProMat_KMU/ BMBF	https://www.bmbf.de/bmbf/de/forschung/innovativer-mittelstand/kmu-innovativ/kmu-innovativ-materialforschung-promat_kmu/kmu-innovativ-materialforschung-promat_kmu.html
ICT for electromobility: economical e-vehicle applications and infrastructures	BMWK	https://www.digitale-technologien.de/DT/Navigation/DE/ProgrammeProjekte/AktuelleTechnologieprogramme/IKT-EM/IKT-EM-3-Foerderprogramm/foerderung.html
Central Innovation Programme for SMEs (ZIM)	BMWK	https://www.zim.de/ZIM/Navigation/DE/Foerderangebote/Kooperationsprojekte/kooperationsprojekte.html
Federal funding for energy and resource efficiency in the economy (EEW) - Module 5: Transformation concepts	BMWK	https://www.bafa.de/DE/Energie/Energieeffizienz/Energieeffizienz_und_Prozesswaerme/Modul5_Transformationskonzepte/modul5_transformationskonzepte_node.html
Energy Research Programme - Applied non-nuclear research funding	BMWK	https://www.energieforschung.de/
Federal funding for efficient heat grids (BEW): Module I - Transformation plans, feasibility studies	BMWK	https://www.bafa.de/DE/Energie/Energieeffizienz/Waermenetze/waermenetze_node.html
Federal funding for efficient heating networks (BEW): Module II - Systemic funding (investment and operating costs)	BMWK	https://www.bafa.de/DE/Energie/Energieeffizienz/Waermenetze/waermenetze_node.html
Sales of electrically powered vehicles (environmental bonus)	BMWK	https://www.bafa.de/DE/Energie/Energieeffizienz/Elektromobilitaet/Neuen_Antrag_stellen/neuen_antrag_stellen.html
Federal funding for efficient heating networks (BEW): Module III - Individual measures	BMWK	https://www.bafa.de/DE/Energie/Energieeffizienz/Waermenetze/waermenetze_node.html

Exemplary funding programmes	Funding body	Link
Construction of refuelling vessels for LNG and sustainable renewable fuel alternatives in shipping (Refuelling Vessel RL)	BMWK	https://www.bafa.de/DE/Wirtschaft/Handwerk_Industrie/Betankungsschiffe_LNG/betankungsschiffe_lng_node.html
FH Cooperative	Covenant	https://www.forschung-fachhochschulen.de/fachhochschulen/de/massnahmen/fh-kooperativ/fh-kooperativ_node.html
Decarbonisation in industry	BMUV	https://www.klimaschutz-industrie.de/foerderung/foerderprogramm/
Environmental Innovation Programme (UIP)	BMUV	https://www.umweltinnovationsprogramm.de/foerderinformationen
Supporting the international expansion of green hydrogen production facilities	BMWi and BMBF	https://www.bmwk.de/Redaktion/DE/Downloads/F/20210410-pm-sachstand-foerderrichtlinie.pdf?__blob=publicationFile&v=10
Promotion of measures in the field of export of green and sustainable (environmental) infrastructure	BMUV	https://www.exportinitiative-umweltschutz.de/foerderung/foerderrichtlinie/
HyLand - Hydrogen Regions in Germany	BMDV	https://www.ptj.de/projektfoerderung/nip/hyland-aufruf3
Alternative drives in rail transport	BMDV	https://www.now-gmbh.de/aktuelles/pressemitteilungen/2-runde-des-hyperformer-wettbewerbs-startet/
Production of renewable CNG and LNG fuels via biological methanation	BMDV	https://www.now-gmbh.de/wp-content/uploads/2022/04/Foerderaufruf_Biologische-Methanisierung_20220329.pdf
Market activation of alternative technologies for the environmentally friendly on-board and mobile shore power supply of seagoing and inland vessels	BMDV	https://www.bav.bund.de/SharedDocs/Downloads/DE/Bordstrom/Foerderrichtlinie.pdf?__blob=publicationFile&v=4
Sustainable mobility investment loan (268/269) - For companies	KfW	https://www.kfw.de/inlandsfoerderung/%C3%96ffentliche-Einrichtungen/Kommunale-Unternehmen/F%C3%B6rderprodukte/Nachhaltige-Mobilit%C3%A4t-(268-269)/
IKK - Sustainable mobility (267) - For municipalities	KfW	https://www.kfw.de/inlandsfoerderung/%C3%96ffentliche-Einrichtungen/Kommunen/F%C3%B6rderprodukte/Nachhaltige-Mobilit%C3%A4t-(267)/
Climate protection offensive for small and medium-sized enterprises	Kfw	https://www.kfw.de/inlandsfoerderung/Unternehmen/Energie-Umwelt/F%C3%B6rderprodukte/Klimaschutzoffensive-f%C3%BCr-den-Mittelstand-(293)/
Federal funding for innovative fuel cell heating appliances in buildings	Kfw	https://www.kfw.de/inlandsfoerderung/Privatpersonen/Bestandsimmobilie/F%C3%B6rderprodukte/Energieeffizient-Bauen-und-Sanieren-Zuschuss-Brennstoffzelle-(433)/?redirect=365568
EU		
IPCEI	European Commission	https://single-market-economy.ec.europa.eu/industry/strategy/hydrogen/ipceis-hydrogen_en
InvestEU	European Commission	https://www.eib.org/de/products/mandates-partnerships/investeu/index.htm
Horizon Europe Framework Programme (closed)	European Commission	https://cinea.ec.europa.eu/programmes/horizon-europe_en

Exemplary funding programmes	Funding body	Link
Innovation Fund Large Scale Projects	European Commission	https://cinea.ec.europa.eu/funding-opportunities/calls-proposals/innovation-fund-third-large-scale-call-projects_en
KDT JU Key Digital Technologies Joint Undertaking	European Commission	https://www.kdt-ju.europa.eu/current-call
Circular bio-based Europe - Joint Undertaking	European Commission	https://www.cbe.europa.eu/open-calls-proposals
Clean Aviation - CAJU	European Commission	https://www.clean-aviation.eu/clean-aviation/participation/calls-for-proposals