H2morrow

The Potential of Hydrogen for Decarbonization of German Industry

A joint study by Equinor and OGE
Management Summary

equinor

Open Grid Europe
The Gas Wheel

1. Intro

In the past year, Equinor and Open Grid Europe (OGE) have examined the development of a complete value chain for clean hydrogen based on decarbonized natural gas. The screening study concludes that the joint project H2morrow can feasibly supply large quantities of hydrogen to industry and other end-users in North Rhine-Westphalia by 2030. This can significantly contribute to the successful decarbonization of the German industry. The groundbreaking project will be developed further by Equinor and OGE and will involve potential anchor clients and other partners in an upcoming second phase.

Germany has already achieved important milestones in implementing the energy transition, especially in the electricity sector. However, many areas of industry that depend on reliable, energy supplies in baseload quantities around the clock still face great challenges to decarbonize. In order to meet its targets under the Paris accord, Germany has committed itself to achieve to climate neutrality by 2050 - without jeopardizing its economic and innovative power. H2morrow can help fill this gap and deliver base-load hydrogen in the required quantities. Hydrogen from natural gas provides security of supply as there are no bottlenecks due to external factors such as weather or transmission network utilization. The prerequisite is the creation of a supra-regional transport infrastructure based on extensive reuse of existing pipeline systems.

Current studies are aiming to demonstrate that hydrogen can be added to distribution grids at up to 20 percent by volume in order to reduce emissions in the heat supply. In addition, the energy lends itself for use in many areas of the mobility sector - whether in heavy goods or public transport. In the medium to long term, experts estimate the German hydrogen demand to reach three-digit terawatt levels.[1] In order to ensure a stable supply and to be able to respond to peaks in demand, Germany must make use of a whole range of sources. These include hydrogen from renewable electricity with electrolysis, especially from northern Germany, hydrogen from decarbonized natural gas and hydrogen from direct imports.

The climate-friendly characteristics of hydrogen contribute to its renewed rise in popularity as a key fuel for the energy transition. However, to finally bring the technology to fruition, it takes pioneers to produce large quantities of climate-friendly, affordable hydrogen in order to establish a scalable and liquid market. This is where H2morrow comes in to push the development of an efficient and diversified hydrogen market with security of continuous supply – also by creating large transport infrastructures linking sources and drains of the market.

[1] DWV, 2018. Integriertes Energiekonzept 2050, see https://www.dwv-info.de/wp-content/uploads/2019/08/iek-2050.pdf

2. At a glance

8,6 terawatt hours (TWh) of hydrogen for **industry** and households in NRW

50-80 euros per megawatt hour (MWh) of hydrogen

process has an **energy efficiency** **of 80%**

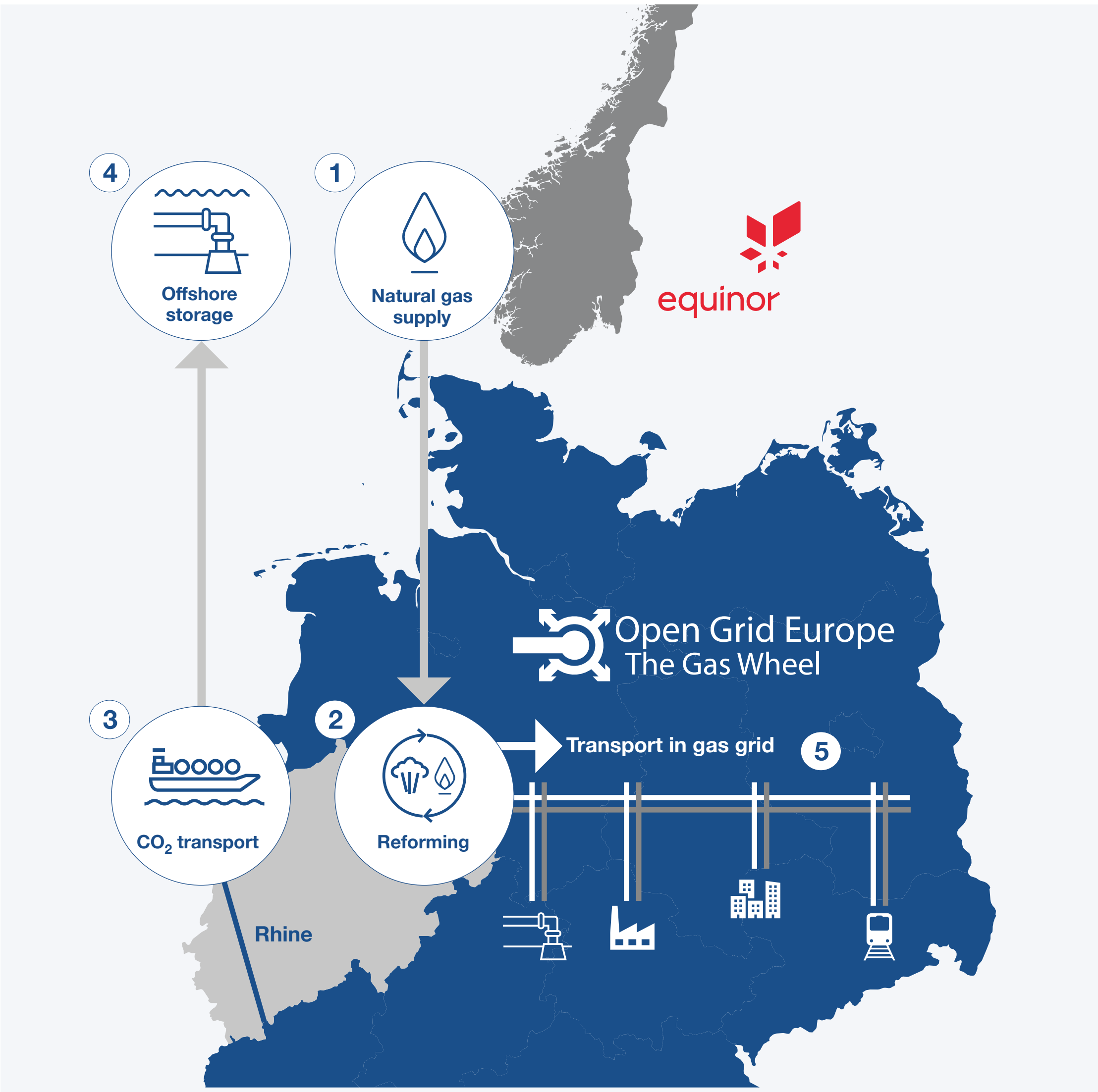
entire supply chain ready for use by **2030**

1,9 million tons of CO_2-emission reductions per year

1 gigawatt (GW) reformer

pilot project in **North Rhine-Westphalia (NRW)**

95% lower carbon **footprint**



1. Natural gas is supplied from Norway.
2. Natural gas is converted to hydrogen by autothermal reforming; the incurring CO_2 is captured.
3. The liquefied CO_2 is transported to Norway by ship.
4. There, the final and safe CO_2 storage takes place 120 km offshore and more than 2000 meters below the seabed.
5. The hydrogen is fed into the gas network of OGE. It is transported via pure hydrogen pipelines.

Source: H2morrow

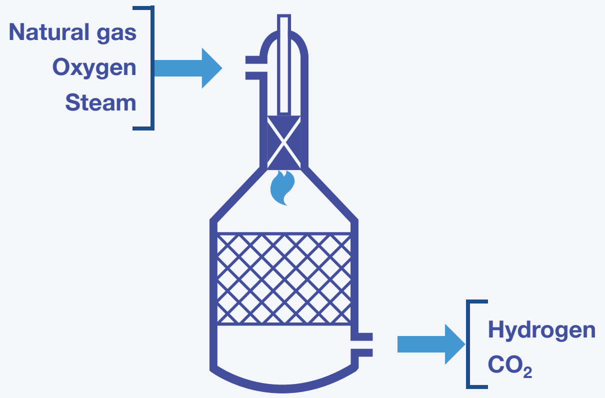
3. Project Overview

3.1 Hydrogen from Natural Gas

In the current hydrogen debate, it is often forgotten that hydrogen has been widely used as an industrial raw material for decades. However, this hydrogen is not produced by electricity through electrolysis, but via fossil fuels, usually from natural gas. 96 percent of the hydrogen produced worldwide today is produced in a steam reforming process.

The established method has been used for decades on a large industrial scale. However, the hydrogen produced this way includes no carbon capture and is therefore not carbon-neutral. In the traditional steam reforming process, the by-product CO_2 is emitted into the air. Although conventional steam reforming can be combined with CO_2 capture, this is associated with higher costs due to the conversion of many individual production steps.

Hydrogen from decarbonized natural gas



Autothermal reforming produces hydrogen based on natural gas.

Source: H2morrow

That is why H2morrow uses an optimized process called autothermal reforming (ATR). Here, natural gas is reformed to hydrogen with steam and pure oxygen under high pressure. By adding oxygen, this process is autothermal, i.e. no additional heat input is needed. This has two advantages: on the one hand, the methane can be converted into hydrogen even more efficiently, on the other hand, the by-product CO_2 is under a higher partial pressure, i.e. higher concentration than in traditional steam reforming. This makes it more cost-efficient to capture and sequestrate. The

ATR process with CO_2 capture reduces the carbon footprint of the resulting fuel by 95 percent.

An autothermal reformer runs with an energy efficiency of around 80 percent. In comparison, state-of-the-art electrolyzers run at around 70 percent. The concept of H2morrow is to build a reformer with a size of 1 gigawatt. As demand increases, more reformers can be added modularly at a lower cost, since the infrastructure for hydrogen and CO_2 handling is already in place. Thanks to the secure supply of natural gas, such a reformer can provide a base load hydrogen supply of 8.6 terawatt hours per year. This corresponds to the yearly energy requirements (electricity and gas) of 450,000 average households.

Finally, autothermal reforming also offers advantages when it comes to finding a suitable location, since the plants require less space than conventional steam reformers.

3.2 Infrastructure

Hydrogen can be used in the existing gas infrastructure, which is not only more efficient and economical, but also faster to implement than the construction of new pipelines. Hydrogen can either be blended with natural gas or used as a pure product. The use of pure raw materials has many advantages over blending in later use. Specific customer groups require very low or, in the future, very high hydrogen content. These needs can be met by a targeted, customer-specific mixture of pure hydrogen and pure natural gas.

Furthermore, the hydrogen content in the natural gas network cannot be precisely controlled when blended: If, for example, 10 percent hydrogen is fed into the grid at a certain point, the multiple possible transport routes cannot guarantee a constant concentration at various exit points. The hydrogen content at one exit point then could amount to 5 percent and maybe even just 2 percent for another customer with a longer transport distance. However, end users and their systems are dependent on a constant and calculable gas quality at all points of the network. As a result, OGE has explored the possibility of fully converting natural gas pipelines for hydrogen use.

One of the pilot regions identified is currently mainly supplied by low calorific - so-called L-gas - from the Netherlands. Due to the decreasing production there, it must be replaced by high calorific - so-called H-gas - no later than 2030. This H-gas is transported from other sources into the region and accordingly uses other transport routes. This shift in gas supply creates a unique opportunity: previously used infrastructure for the transport of L-gas can be used in part for a new hydrogen infrastructure.

In the pilot region, many pipelines are also laid in parallel, i.e. with two or more strands. These strands do not necessarily lie in the immediate vicinity but can also run many kilometers apart from each other. After the H-gas conversion, one strand in these parallel pipelines may carry hydrogen while the other continues to supply natural gas. This approach creates utmost flexibility for all connected customers and network operators. With this approach, tailor-made solutions can be found for all customers, since the hydrogen can either be delivered pure or mixed in a controlled manner. If desired, industrial customers can swiftly switch to 100 percent hydrogen. Distribution network operators with many household customers can add the desired amount of hydrogen to the heating network in a controlled manner, while customers with highly sensitive production processes can continue to source natural gas. In this way, maximum consideration can be given to individual investment cycles and production conditions whilst the decarbonization path can be defined together with the end users.

Technical conditions for conversion

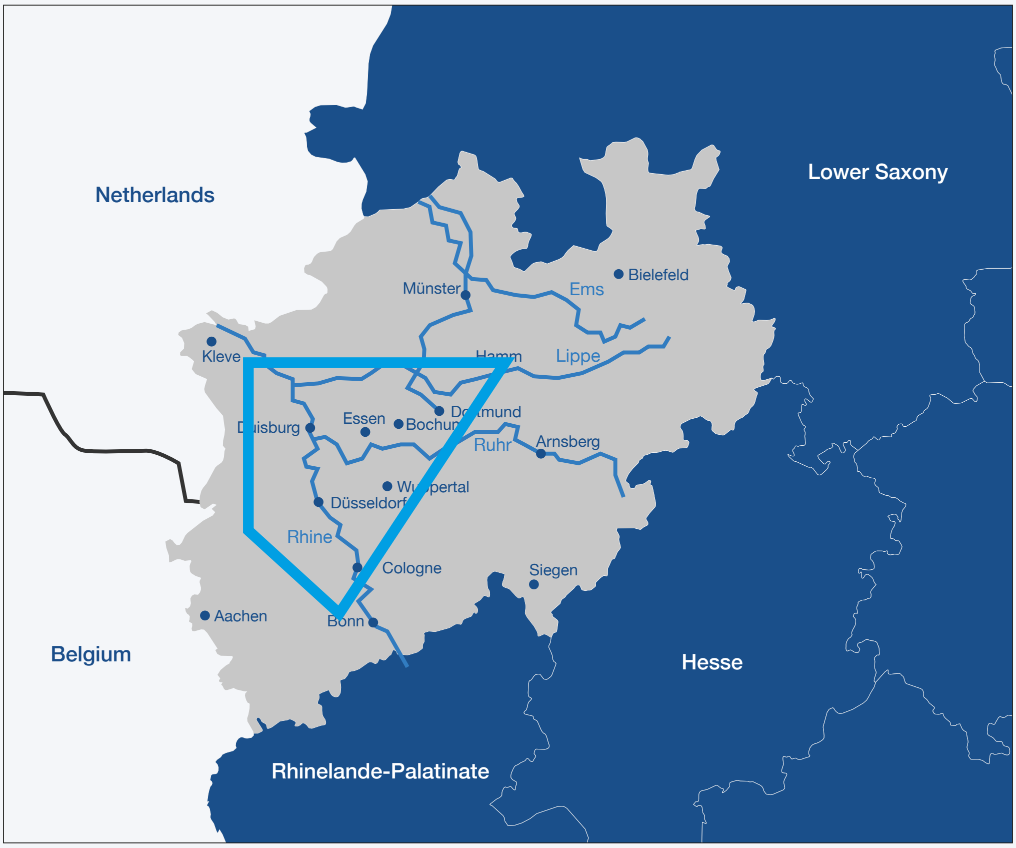
The pre-requisite for this change is that today‘s natural gas pipelines are technically capable of transporting hydrogen in the future. For this process, the operating experience with so-called town gas can be used. This gas was produced by coal gasification and had a hydrogen content of 55 percent. Town gas was used until well into the 1970s in many parts of Germany. Hence, large parts of the German natural gas infrastructure have already transported gas with high hydrogen content in the past.

OGE has reviewed a conversion of selected pipelines to 100 percent hydrogen in and can confirm the technical feasibility of the project. During the conversion, the pipelines themselves as well as the individual components, such as compressor units or seals, are tested by independent experts. Depending on the results of the material testing, individual components might have to be replaced or adapted for hydrogen use. After new and independent testing, the pipelines will be approved by the proper authority for the use of hydrogen. The full conversion will be executed in cooperation with the competent authorities within a five-year period with costs well below the level of newly built infrastructure.

3.3. Location

H2morrow wants to offer a solution for the successful decarbonization of industry which can be implemented quickly. North Rhine-Westphalia, the industrial heartland of Germany, was chosen as a possible, future project location.

Possible pilot region in North Rhine-Westphalia



North Rhine-Westphalia is a potential, future project location.

Source: H2morrow

A plethora of carbon-intensive industries are located here, including the steel industry, chemical parks and refineries, just to name a few. Overall, the region has a decarbonization potential of over 59 million tons of CO_2 equivalent among the largest industrial emitters alone - not including power plants. This includes companies that use natural gas today and want to switch their supply to pure hydrogen. Even for industries that currently burn coal, a hydrogen supply offers a real alternative.

H2morrow is currently discussing the project with some of these companies. For example, a Memorandum of Understanding has been signed with ThyssenKrupp Steel to investigate the integration of climate-friendly hydrogen into the company‘s future production processes.

Last but not least, the Rhine-Ruhr metropolitan area is the most densely populated region in Germany with around 10 million inhabitants. The cities are connected by a dense public transport network; busses and not yet electrified railway lines represent additional perspectives for end-users.

Moreover, the industrial region is well developed thanks to a dense pipeline infrastructure, and the aforementioned L/H gas conversion offers a unique opportunity for the project. The local availability of salt caverns, which can be used for seasonal hydrogen storage, completes the picture. A further significant factor is the vicinity to the Rhine, since inland shipping routes are central to the project’s planned CO_2 logistics chain.

3.4. CO_2 Value Chain

CO_2 is a by-product of the reforming process. When it is captured and stored long-term, hydrogen production becomes nearly climate-neutral (95 percent emission reduction).

CO_2 is separated and captured during the reforming process and purified in a next step. To make transport easier, the gas is liquefied at about -50 ° C in a liquefaction facility next to the ATR. After liquefaction, the CO_2 is pumped into an intermediate storage before being loaded onto barges. CO_2 barges finally transport the gas on the Rhine to Rotterdam.

There, the CO_2 is reloaded onto larger ships, which then unload the CO_2 at a terminal in Kollsnes on the Norwegian west coast. Thereafter, the CO_2 is fed into a 120 kilometers long offshore pipeline, through which the CO_2 reaches the subsea template, where the CO_2 is pumped down more than 2000 meters into a saline aquifer for permanent storage.

The transport of CO_2 via ship is not uncommon and regularly used, for example, in the food or beverage industry. However, CO_2 is usually traded in smaller quantities. Hydrogen production with a reformer of the order of 1 gigawatt generates around 1.9 million tons of CO_2 per year.

In order to handle these quantities and to transport them to Rotterdam at regular intervals, around 9 trips per week in barges with a transport capacity of 3,500 cubic meters will be required. Gas carriers with a capacity of up to 30,000 cubic meters of CO_2 are likely to be used for the transportation from Rotterdam to the terminal at Kollsnes on the west coast of Norway. With this size of gas carrier, about one voyage every 6 days would be required. Gas carriers of this size are not yet used for CO_2 transportation, and the project is currently examining the development of suitable vessels, for example by converting existing LPG carriers to be used for CO_2 transport.

The port of Rotterdam is planning to invest in several CO_2 projects with various partners and aims to develop a large CO_2 hub. Rotterdam therefore lends itself well for H2morrow project logistics. The declared goal of the project partners is to benefit from synergies with similar projects, for example in the Netherlands, Great Britain and in Norway, in order to make optimal use of logistical hubs as well as gas carriers for ocean transport.

CO_2 will be transferred from the Rotterdam hub to the Kollsnes terminal and then by offshore pipeline into a designated deposit on the Norwegian Continental Shelf for permanent storage. The Northern Lights project, sponsored by the Norwegian government and developed in cooperation with other European energy companies, including Equinor, is the base case for H2morrow. The transport by ship lends itself to the planned quantities and transport routes of the H2morrow project and matches the envisaged capacities of the planned Northern Lights CO_2 infrastructure.

3.5. CCOS – Carbon Capture and Offshore Storage

For the achievement of global climate goals, the permanent subsurface storage of CO_2 will play a significant role. According to many experts, the technology is an essential building block in the portfolio of a decarbonized energy supply. For example, in the “Special Report: Global Warming of 1.5 °C”, the IPCC lists CCS as a measure to achieve the 1.5-degree target.[2]

The use of these technologies is even more urgent, as there have not been significant emission reductions on a global level in recent years. The International Energy Agency (IEA) estimates that 14 percent of emissions must be captured and stored in order to meet Paris‘ climate targets, not to mention a zero-carbon society.[3]

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[2] IPCC, 2018. Special Report, Global Warming of 1.5 °C, see https://www.ipcc.ch/sr15/

[3] International Energy Agency, 2017. Energy Technology Perspectives 2017, see https://webstore.iea.org/energy-technology-perspectives-2017

The technology is not new but is already used successfully worldwide in many places. H2morrow uses CCOS (Carbon Capture and Offshore Storage), the capture and subsequent storage of CO_2 under the seabed in saline aquifers in the Norwegian North Sea.

Worldwide, the IPCC estimates offshore storage capacity at over 2 trillion tons.[4] The North Sea offers optimum geological conditions for this purpose. There are potential deposits with enormous capacities, mostly found on the Dutch, British, Danish and Norwegian continental shelves. The Norwegian part of the North Sea alone has enough capacities for more than 67 billion tons, which is equivalent to storing 80-times of German total CO_2 emissions in the year 2018. The large-scale operation of CO_2 deposits is also favored by its proximity to European industrial centers and Norway's decades of experience in offshore operations.

When stored in the Norwegian continental shelf, CO_2 is not, unlike often suspected, stored in former natural gas deposits, but in special rock strata, saline aquifers. These are porous sandstone layers that carry saltwater. Through the permeable sandstone, the CO_2 can be optimally distributed in the deposit. Suitable formations also have an extensive covering layer of impermeable rock, which acts as a seal and prevents leakages. The stored CO_2 partly dissolves in the saltwater of the rock layer and is partly embedded in the pores of the rock. In the long term, the dissolved CO_2 in the water reacts with the rock of the deposit and solidifies. As a result, the CO_2 is permanently trapped in a solid rock. Incidentally, natural gas fields used today were created in the same way: Natural gas molecules were deposited in porous rock millions of years ago and were embedded there.

CCOS has been successfully used by Equinor for more than 20 years, in line with Norwegian and EU CO_2 storage directives, primarily to store surplus CO_2 from natural gas production. To date, Equinor has safely transported and stored over 20 million tons of CO_2 under the seabed of the North Sea and the Barents Sea. The deposits are monitored, and no CO_2 leaks have been observed or detected. The procedure is firmly established in Norway and is supported by the state and society at large.

Once the CO_2 is fed in, its whereabouts in the deposits are closely controlled. Seismic controls are accurately monitoring where the CO_2 is located. This data is shared by Equinor with scientists and partners worldwide. So far, no safety risks or health and environmental impacts have been identified.

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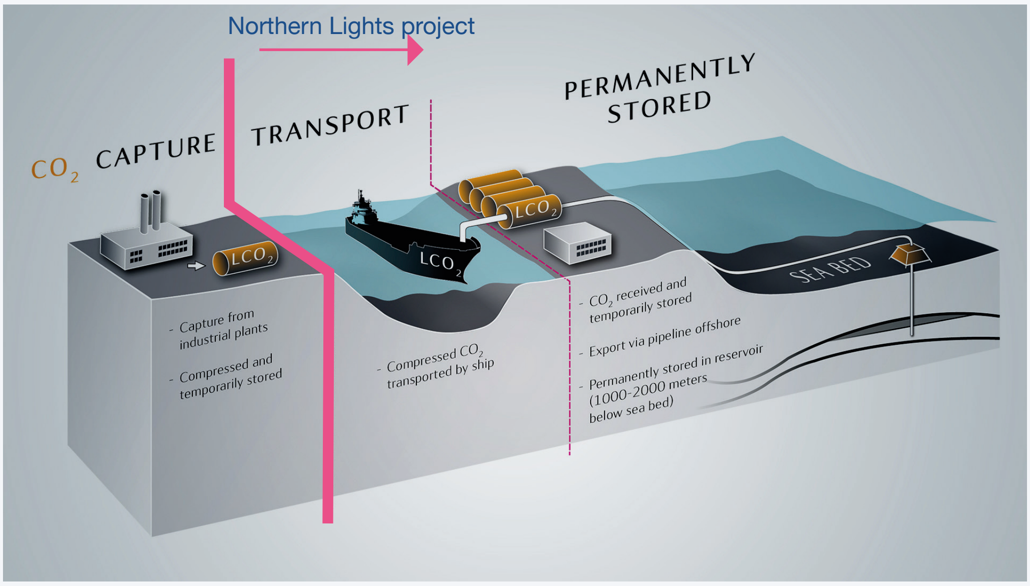
[4] IPCC, 2005. Special Report: Carbon Dioxide Capture and Storage, see https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_summaryforpolicymakers-1.pdf

Safe CO_2 storage as part of the Northern Lights project



Equinor has more than 20 years of experience in CCOS and is partner of the Northern Lights project. The project plans to set up the first complete value chain for transport and offshore storage for industrial CO_2 emissions.

Source: Gassnova

The Northern Lights project is the base case deposit for CO_2 from the H2morrow project. The commissioning of the project to store industrial CO_2 emissions from all over Europe is scheduled at the end of the year 2023, which means that logistics and transport chains will be firmly established well in time for the start of H2morrow.

3.6. Regulation

The current international legal framework poses barriers to the implementation of H2morrow and similar projects in Germany. Furthermore, hydrogen must be considered technology-neutrally and comprehensively in German legislation in order to reach its full potential for achieving the German climate targets.

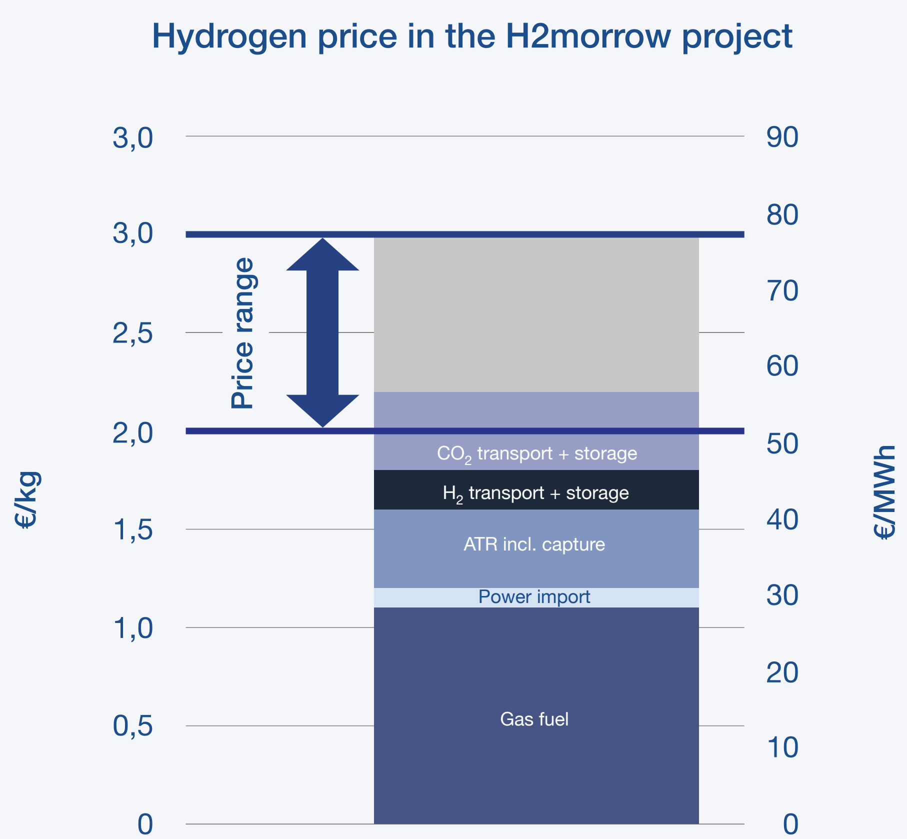
In order to keep the costs in the H2morrow project as low as possible, a cross-border CO_2 supply chain will be necessary. As Norway's large offshore natural gas pipelines can only be converted to hydrogen in the longer term, natural gas will have to be reformed to hydrogen in Germany. The separated CO_2 thus must be transported across national borders for safe offshore storage abroad.

This transport is regulated in the London Protocol of 1972. The agreement has already been amended to allow CO_2 transport for storage. However, most signatories, including Germany, have not yet ratified the amendment. Alternatively, the conclusion of bilateral or multilateral agreements between participating states can be a way of facilitating transport.

4. Base Case: Prices and Costs

The price for the hydrogen produced in the H2morrow project consists of several components. Overall, a price of around 50-80 euros per megawatt hour or 2-3 euros per kilogram of hydrogen can be estimated. The CO_2 costs of the project are within a range of 50-70 euros per ton. The main components of the costs are the natural gas price, the CO_2 liquefaction, transport, and offshore storage as well as the capital costs for the ATR. Further costs arise from the energy requirements of the reformer as well as the hydrogen infrastructure. The most sensitive component in this estimate is the gas price, which heavily depends on future developments in the global energy market. H2morrow uses assumptions for the natural gas price development based on the forecasts of the independent Norwegian certification institute DNV GL.[5]

The investment needs for the construction of the ATR, the liquefaction of the CO_2 and the conversion of the pipeline infrastructure as well as the development of a CO_2 logistics are estimated at around 1 billion euros.



The components of the hydrogen price for H2morrow.

Source: H2morrow

[5] DNV GL, 2019. Hydrogen in the electricity value chain, see https://www.dnvgl.com/publications/hydrogen-in-the-electricity-value-chain-141099

5. Hydrogen and the Future German Energy Mix

Although Germany's emissions are declining, its pace is far too slow. According to the Federal Environment Agency (UBA), the annual reduction will have to be more than tripled in order to reach the 2030 targets.[6] It is also clear that the longer the necessary measures are postponed, the more expensive it will be to achieve the set goals.

H2morrow and hydrogen from decarbonized natural gas can make a significant contribution to enabling massive CO_2 savings in a relatively fast time frame. In addition, a pilot project of this size enables the fast ramp-up of a hydrogen market. This also supports electrolysis plants and suppliers of renewable hydrogen: smaller projects benefit from already established sales, transport and distribution structures.

Although the benefits of hydrogen are currently being discussed intensively as the key to an efficient energy transition in Germany, at the same time there are only a few reliable energy scenarios that reflect its extensive use. As part of the H2morrow project, a development of the German energy mix including hydrogen has been modeled.

Based on the current composition of the German energy mix, coal (hard coal and lignite) and nuclear energy will fall out of the energy mix in the medium term as already decided by the German government. The model works under the assumption that from 2022 nuclear energy and from 2038 coal will no longer be used for energy production.

The lack of electricity generation capacity (2017: net output of coal 42.6 GW, net output of nuclear energy ~ 10 gigawatt) will be replaced by declining electricity demand thanks to continuous efficiency measures, the massive expansion of renewable energies and complementary natural gas power plants. Natural gas consumption will fall sharply in the long term but will continue to play a role for a very long time for back-up power generation.

From the mid-2020s, the industry's transition to hydrogen will begin. Hydrogen from decarbonized natural gas will play an important role here because of the high volumes that must be provided on an ad-hoc basis. The high demand for hydrogen in the industry, combined with the corresponding construction of hydrogen logistics and storage to secure supply, is leading to increasing demands in other sectors, such as mobility, power generation and, to a lesser extent, the household heating market.

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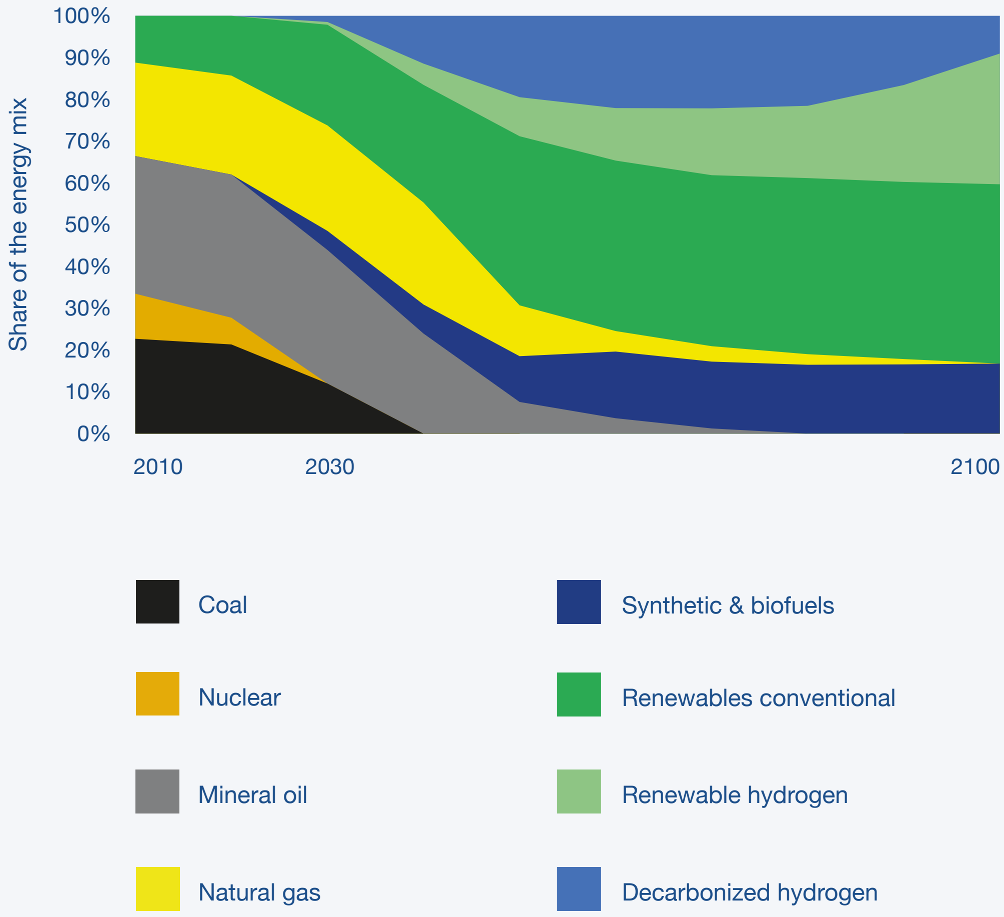
[6] Federal Environment Agency, 2019. European energy and climate goals, see https://www.umweltbundesamt.de/daten/klima/europaeische-energie-klimaziele

A potential German energy mix including hydrogen



Model of a possible German energy mix including hydrogen.

Source: H2morrow

This development on the demand side is preparing the market for a worldwide ramp-up of renewable hydrogen. To meet this demand, imports to Germany in larger quantities from countries with higher solar and wind resources will be necessary. The increasing run-up of hydrogen from renewables will supplement and replace hydrogen from decarbonized natural gas if enough and competitive volumes are achieved. In addition to the directly saved emissions, H2morrow also provides the impetus for important further innovations and a broad and diversified hydrogen industry by providing the necessary infrastructure.

The energy mix is complemented by the growing production and import of biomethane as well as liquid biofuel and synthetic fuels, which are gradually replacing the use of mineral oil in Germany. Domestic production will take place but only to a limited extent. According to dena, the German potential for biomethane is 100 terawatt hours per year (current feed into the gas grid: 9 terawatt hours per year).

The modeling thus confirms the results of the dena study „Integrated Energy Transition“ of 2018, according to which a technology mix reduces the costs of the *Energiewende* and achieves climate targets more quickly.[7] Hydrogen from decarbonized natural gas enables system stability at a lower cost, especially during the initial phase of the transition. The best cost-benefit effects over the long term are achieved in conjunction with renewable hydrogen.

[7] dena, 2018. „Integrated Energy Transformation“, see https://www.dena.de/fileadmin/dena/Dokumente/Pdf/9261_dena-Leitstudie_Integrierte_Energiewende_lang.pdf

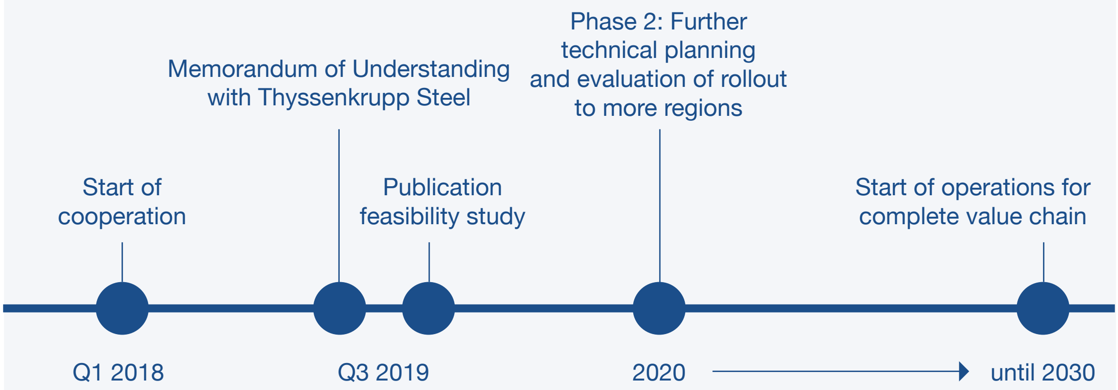
6. Outlook

In the first 18 months since the beginning of their collaboration, Equinor and OGE have demonstrated that hydrogen from decarbonized natural gas can be produced in large quantities at a reasonable cost in Germany and made available to the market. Significant CO_2 saving potentials for German industry can be realized in a relatively short period of time.

In the next phase of the collaboration, talks will be held with potential future industrial customers. In addition, the technical details of the plant, infrastructure and CO_2 logistics will undergo refined analysis. The regulatory barriers to a successful implementation of the project shall be overcome. The full value chain of the project could be put into operation by 2030 the latest.

The pilot project should only be the impetus for a large-scale, diversified hydrogen industry in Germany. The project partners aim to explore the extension of the hydrogen network in conjunction with other stakeholders. Together, they will determine how large parts of Germany and the neighbouring states can be supplied with hydrogen to create a truly European hydrogen grid.

The H2morrow Timeline



The complete value chain shall be put in operation by 2030 the latest.

Source: H2morrow

The project partners

Equinor ASA

Equinor is an international energy company, Europe‘s second largest gas supplier and the largest operator of offshore gas and oil production facilities. A rapidly growing portfolio in offshore wind and solar energy marks signifies Equinors evolution to a broad energy company. Equinors current offshore wind portfolio can supply more than one million European homes with renewable energy.

Open Grid Europe GmbH (OGE)

Open Grid Europe operates the largest transmission network in Germany with a length of around 12,000 km. The approximately 1,450 employees throughout Germany ensure safe, environmentally friendly and customer-oriented gas transport. Through cooperation with European transmission system operators, OGE creates the conditions for cross-border gas transport and trade. As a customer and service-oriented provider, the company actively supports the energy transition by continuously improving infrastructures and minimizing risks.

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