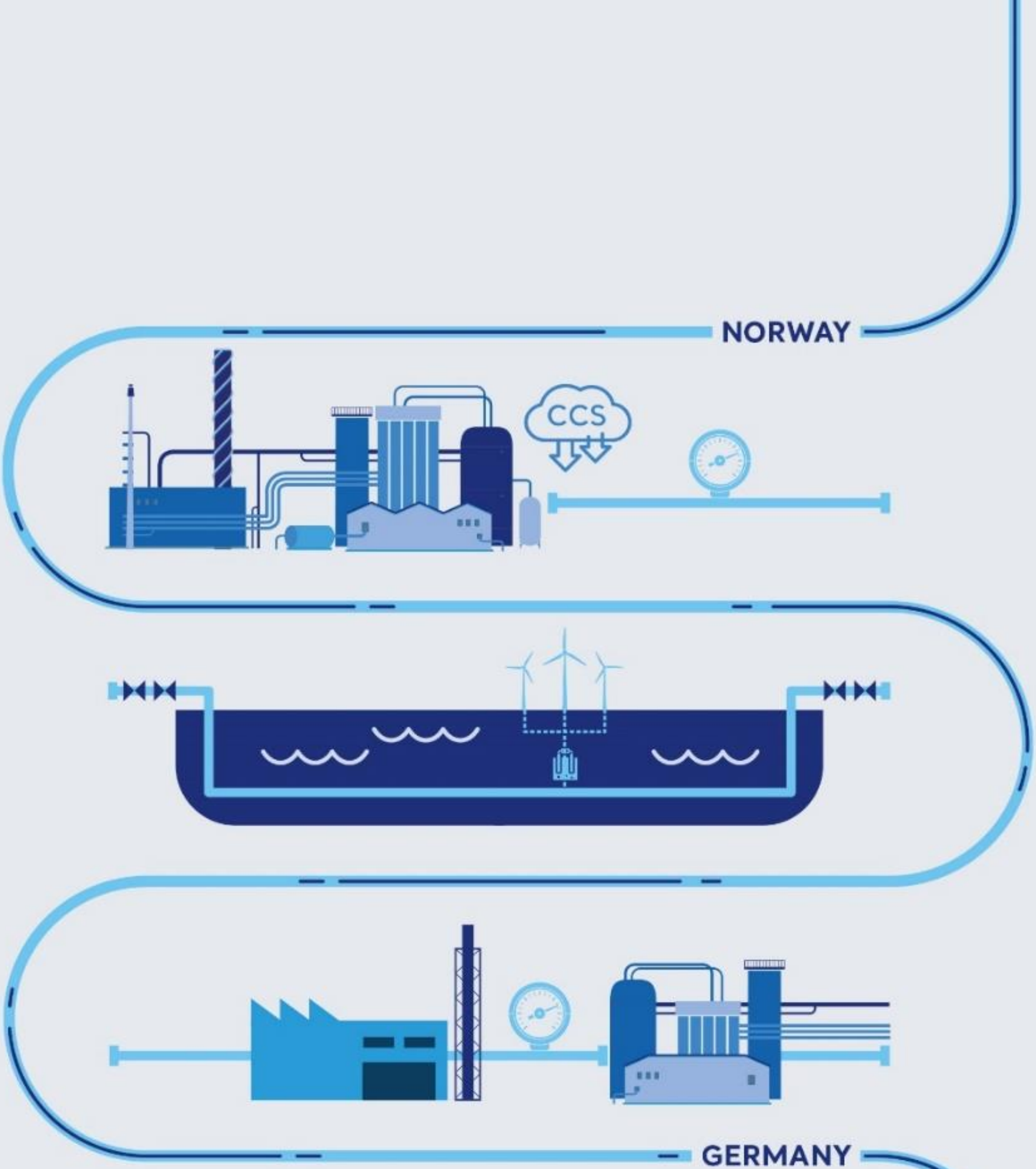

German-Norwegian Energy Cooperation Joint Feasibility Study

Hydrogen value chain summary report

GASSCO

dena
German Energy Agency

Publisher

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1 Executive summary

On behalf of the German and Norwegian Governments Deutsche Energie Agentur (dena) - the German Energy Agency - and Gassco have conducted a feasibility study on a hydrogen value chain from Norway to Germany.

The objective of the study has been to verify the viability of a German-Norwegian hydrogen value chain; hence the study framing covers the whole value chain, from potential hydrogen production in Norway to consumers in Germany. The work has been based on input from industry-driven projects at a scale large enough to establish a hydrogen value chain from Norway to Germany, starting in 2030. Most parts of the industry projects of the hydrogen value chain are still in the early stages of project development, but some of the German hydrogen consumers are more mature i.e. the steel industry.

Based on the definitions of the EU Commission[1], this report refers to low-carbon hydrogen and renewable hydrogen instead of blue and green hydrogen. Low-carbon hydrogen in this report refers to hydrogen produced from natural gas with CCS with an ultra-low carbon intensity[2] (below 1 kg CO_{2e}/kg H_2), and renewable hydrogen refers to hydrogen produced through the electrolysis of water powered by electricity from renewable sources.

The hydrogen framework in Germany differs in the various parts of the value chain with respect to the production pathways. While the infrastructure parts mostly make no difference between low-carbon and renewable hydrogen, the funding programs for both production and offtake do make a difference. When the two different types are explicitly named, renewable hydrogen is always favoured over low-carbon hydrogen.

The establishment of pipeline infrastructure for hydrogen transport from Norway to Germany must be based on a need to transport large quantities of hydrogen, in the order of millions of tonnes per year. Hydrogen production at this scale starting in 2030 could be realised based on low-carbon hydrogen, under the assumption that there is a basis for commercial commitment. This could in turn form a basis and include the transport capacity for the less mature renewable hydrogen production projects, that are at a scale relevant for pipeline transport. Currently, the most mature renewable hydrogen projects are small-scale and located in remote areas.

Pipeline transport of hydrogen from Norway to Germany is considered technically feasible within 2030. There is, however, a need for qualification of technology, such as compressors, valves and flow meters. This qualification can have an impact on the timeline as well as the cost. Additionally, there are other issues, such as clarification of regulatory model, technical and regulatory codes, standards and guidelines for cross-border offshore H_2 pipelines, that need to be in place.

The integration of Norwegian hydrogen imports into the German hydrogen pipeline network could be possible without delays and without increased overall network costs. The German core network is planned to be regulated. The grid charges and further grid planning necessary to integrate increasing imports from Norway into the German grids are planned available by the end of 2023. Under the assumption that the grid fees will be set in a regulated manner and will be the same throughout Germany, there will be no disadvantages for the first consumers, regardless of their location.

The projected demand for hydrogen in Germany will exceed the domestic production volumes for hydrogen already before 2030. Import will be necessary in all German demand scenarios, both short-term and long-term. Even though these demand scenarios are associated with uncertainty, the

[1] (Commission, u.d.)
[2] (WBCSD, 2021)

customers in Germany assume that it will hardly be possible to cover the demand with renewable hydrogen at the beginning of the market ramp-up. As such, the purchase of low-carbon hydrogen is expected to be necessary and therefore desirable.

The major customers in Germany see low to zero technical hurdles in the use of hydrogen, but clear economic ones, which can be overcome by subsidies from the German state. Some of the large projects on the consumer side are awaiting final approval of IPCEI funding. Once this is approved, these projects are planning to make final investment decisions. Several projects will start by converting their plants first to natural gas and then to hydrogen, which reduces risks such as delayed grid connections. The cost difference between the current use of fossil alternatives and low-carbon and renewable hydrogen use can be closed by the climate protection contracts, which are based on the concept of Carbon Contracts for Difference (CCfD), for the projects that are eligible for governmental support. Both the CCfD funding program and the update of the National Hydrogen Strategy state the importance and possible use of low-carbon hydrogen. These measures combined would enable the consumer to enter into a commercial commitment with producers of low-carbon hydrogen. Therefore, it can be assumed that low-carbon hydrogen will initially cover an essential share of the German demand. The share of renewable hydrogen is expected to increase. Since the total demand will increase, low-carbon hydrogen will remain in the market as long as it is cost-competitive and has a low carbon intensity.

Germany will have a large storage requirement, especially to compensate for the fluctuation of electrolyser outputs. Storage projects are already under development and the first demonstration projects are being implemented. More projects are expected to be initiated as the demand for storage increases.

The results show that a German-Norwegian hydrogen value chain could be feasible based on the following main assumptions:

- A market with the willingness and ability to pay for increased energy costs is established.
- A framework enabling long-term contracts on low-carbon hydrogen is in place.
- The producers can ensure that the low-carbon hydrogen meets all criteria required in support programmes and crediting mechanisms.
- The landfall point in Germany can be implemented quickly and jointly.
- The storage capacities in Germany are sufficient to enable a stable system, with consistent and fluctuating production facilities feeding in.
- The technical uncertainties and development needs along the value chain can be solved and implemented as planned.
- Accelerated approval of the infrastructure can be made possible in all countries concerned, including the core grid in Germany.

2 Background and introduction

German Chancellor Scholz and Norwegian Prime Minister Støre agreed in January 2022 to strengthen the German-Norwegian cooperation around the energy transition and to establish a long-term and structured dialogue in the field of industry and energy. The aim is to achieve shared climate goals, create new green industries and jobs and strengthen energy security. Reflecting on this the focus of the cooperation is on:

- Hydrogen
- Expansion of Renewable Energies
- Negative emissions / CCS
- Green Industry

During Vice Chancellor Dr. Robert Habeck's visit to Norway in March 2022 he signed a joint statement on energy cooperation with Norwegian Prime Minister Jonas Gahr Støre. The statement specified close collaboration with the aim to realise large-scale hydrogen imports from Norway to Germany as soon as possible. Consequently, it was agreed that a joint review was to be conducted on how to make large-scale transport, including via pipeline, of hydrogen from Norway to Germany possible. Both countries commissioned a joint feasibility study on this.

In this context, a virtual round table was held under the co-leadership of Germany and Norway in June 2022, bringing together German customers and Norwegian producers to discuss the potential demand, production, and supply of hydrogen from Norway to Germany. Gassco was appointed by the Norwegian Government to lead and facilitate the Norwegian part of the joint hydrogen value chain feasibility study together with the German counterpart the Deutsche Energie Agentur (dena) - the German Energy Agency, appointed by the German Government.

The objective of the joint feasibility study is to verify the viability of a German-Norwegian hydrogen value chain and increase the maturity of the main elements of the hydrogen value chain to a technical and commercial feasibility level.

Based on the definitions of the EU Commission[3] this report refers to low-carbon hydrogen and renewable hydrogen instead of blue and green hydrogen. Low-carbon hydrogen in this report refers to hydrogen produced from natural gas with CCS with a carbon intensity well below 1 kg CO_{2e}/kg H_2, and renewable hydrogen refers to hydrogen produced through the electrolysis of water powered by electricity from renewable sources.

The conceptual hydrogen value chain infrastructure based on the main building blocks is illustrated in Figure 2-1, i.e., hydrogen production, offshore and onshore transport, storage, and consumption.

[3] (Commission, u.d.)

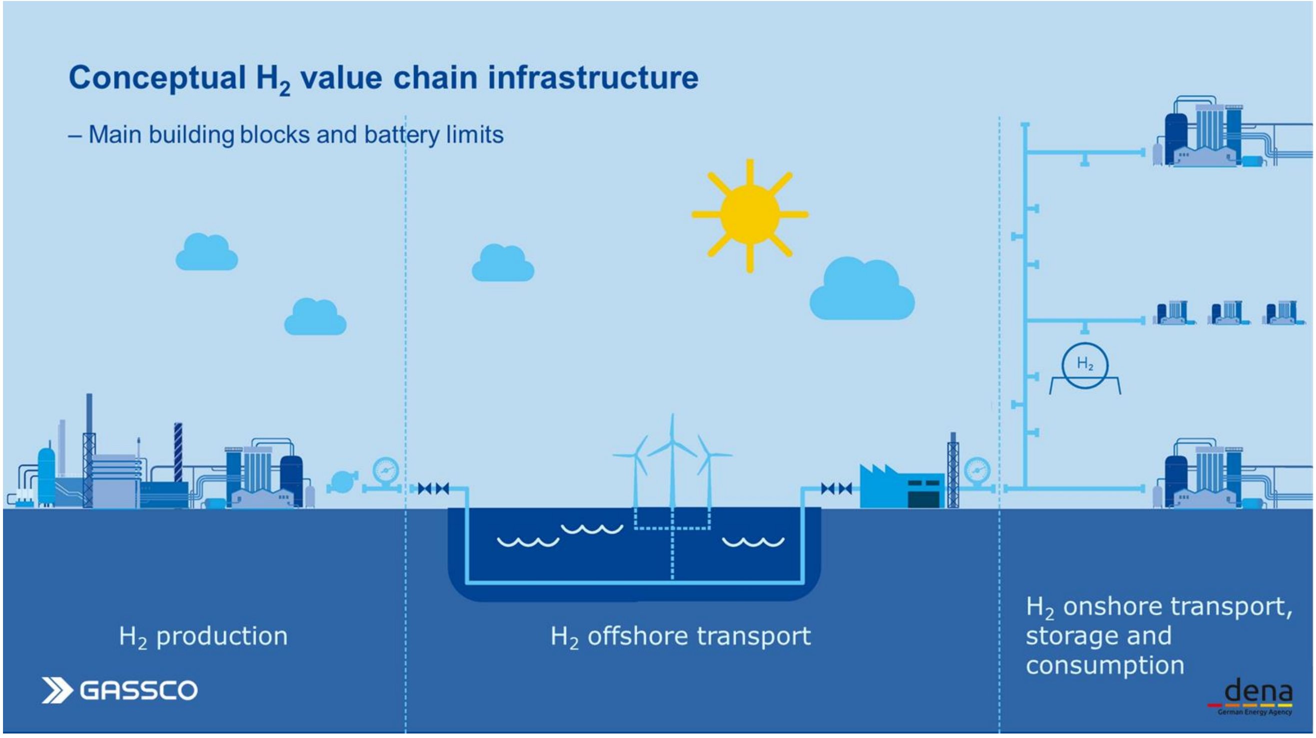

Figure 2-1: Main building blocks for the hydrogen value chain

In the following sections, the organisation of the work is described, as well as an overview of the main output from the main building blocks.

3 Organisation of the joint hydrogen value chain study

Gassco and dena were appointed by the Norwegian and German governments to lead and facilitate a joint feasibility study on a hydrogen value chain from Norway to Germany. The work was organised as shown in Figure 3-1.

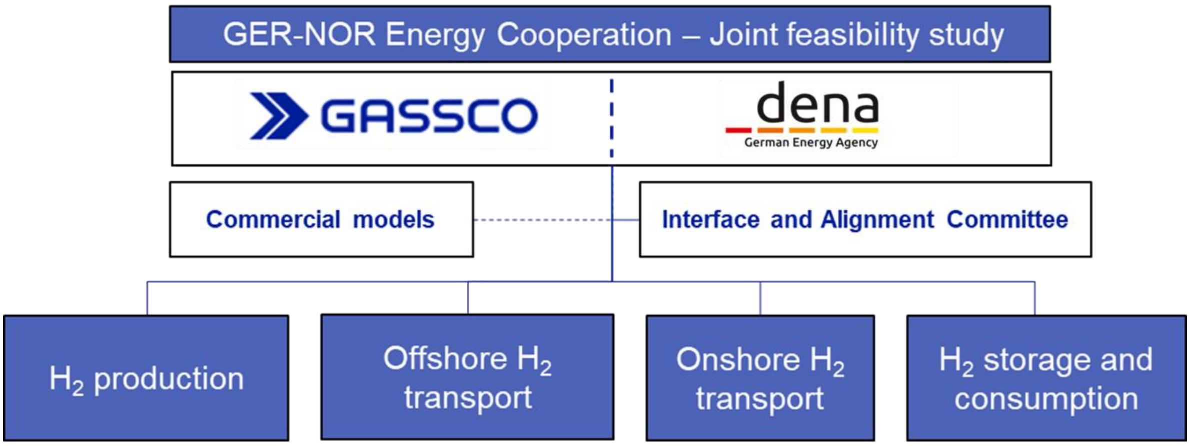

Figure 3-1: German-Norwegian hydrogen joint feasibility organisation

The work streams can be described as follows:
Hydrogen production – Gassco
Mapping of feasibility level large-scale hydrogen production projects in Norway relevant for export to Germany.

Offshore hydrogen transport – Gassco
Feasibility study on behalf of an industry sponsor group of hydrogen pipeline transport from Norway to Germany.

Onshore hydrogen transport – FNB Gas (The Association of Transmission System Operators for Gas in Germany) Network development analyses of onshore hydrogen transport in Germany, including identification of relevant infrastructure projects with an interface to the hydrogen pipeline from Norway.

Hydrogen storage and consumption – dena
Analyses of aggregated hydrogen demand and need for storage in Germany from 2030 to 2040, including identification of large-scale industrial projects by potential consumers of hydrogen in Germany in 2030.

Interface and Alignment Committee – Gassco/dena
Alignment of business drivers, schedule and design basis throughout the hydrogen value chain, with relevant participation from the industry included from all work streams.

Commercial models – relevant information sharing (to Gassco) from the dialogue between Norwegian hydrogen producers and German consumers – this process has not directly been part of the deliverables of the Joint feasibility study.

A similar process for a CO_2 value chain from Germany to Norway was initiated early 2023 and follows the same approach and methodology with regard to the work structure.

4 Hydrogen production in Norway

The content of this section provides an overview of the main production methods for hydrogen as well as a mapping of hydrogen production initiatives in Norway, that are relevant for export to Germany, starting in 2030.

4.1 Production of hydrogen

For hydrogen to be classified as a low- or zero-emission energy carrier, it is essential that it is produced with minimal emissions. This can be achieved through various means, such as water electrolysis powered by renewable electricity (renewable hydrogen) or by integrating carbon capture and storage (CCS) in the reforming of natural gas (low-carbon hydrogen).

Electrolysis is a process where water is split into hydrogen and oxygen, using electricity. To produce one kilogram of hydrogen gas (with an energy content of 33 kWh, (LHV)), approximately 50-55 kWh[4] of electricity is required. However, the actual electricity consumption will depend on the efficiency of the electrolysis system as well as the energy needed for compression to transport the hydrogen. The indirect greenhouse gas emissions associated with hydrogen production via electrolysis depend on the source of the electricity used. If the power source is renewable power this is referred to as renewable hydrogen. In addition to the power input electrolysis requires around 9 litres of water per kilogram of hydrogen produced, according to the fundamentals of chemistry. When considering the additional volume required for water purification and process cooling, an additional ~10-20 L/kg is needed.[5]

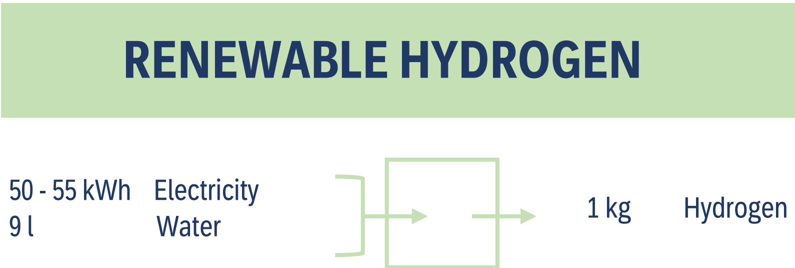

Figure 4-1: Typical input factors for production of renewable hydrogen

There are mainly two commercially available electrolysis technologies in the market today: alkaline electrolysis and polymer electrolyte membrane (PEM) electrolysis. Both technologies are relatively mature but still offer room for further development. The energy loss converting power to hydrogen through electrolysis is around 30-45%.[6]

Natural gas reforming is a process where methane is converted into hydrogen and CO_2. If the CO_2 is then captured and transported to storage this is referred to as low-carbon hydrogen. To produce one kilogram of hydrogen gas, approximately 3.5 kWh of electricity is required, depending on the hydrogen and CO_2 compression need, as well as technologies used for reforming and CO_2 capture. In addition to the power input natural gas reforming typically requires around 3.4 kg of natural gas per kilogram of hydrogen produced, and will produce around 8-10 kg of CO_2.[7] These values are also technology dependent.

[4] (DNV GL, 2019)
[5] (Ramirez, et al., 2023)
[6] (IEA, 2019)
[7] (Pettersen, et al., 2022)

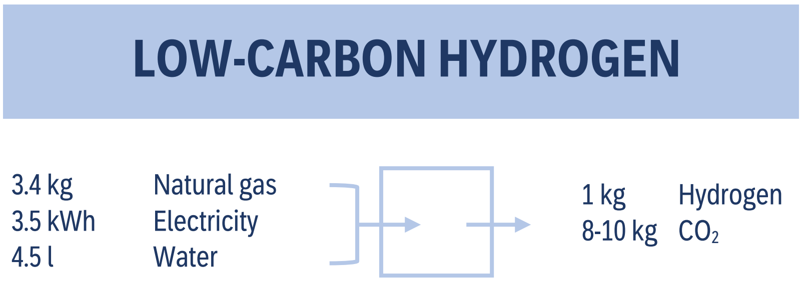

Figure 4-2: Typical input factors for production of low-carbon hydrogen

There are several technologies for converting natural gas into hydrogen. The three most common methods are steam methane reforming (SMR), Partial Oxidisation (POX) and autothermal reforming (ATR), but other technologies are emerging.

High capture rates can be achieved for all three technologies, but for SMR two capture plants will be needed compared to one for POX and ATR. On the other hand, an air separation unit is needed to produce the oxygen used in POX and ATR. This is not needed in an SMR plant.

Water is also needed when converting natural gas to hydrogen. The theoretical minimum for SMR is 4.5 l per kilogram of hydrogen produced, and slightly lower for ATR. However, the need for cooling water etc. will add to this, depending on the plant design.

The expected overall energy loss when converting natural gas to hydrogen, including gas and power consumption, is in the range of 20-30%[8] depending on the choice of technology.

Important factors for producing low-carbon hydrogen are low methane emissions from natural gas production, access to renewable power and close proximity to CO_2 storage. Low-carbon hydrogen produced with a high degree of CO_2 capture, low GHG intensity natural gas feed and a high degree of renewable power can have a carbon intensity well below 1 kg CO_2e/kg H_2.

4.2 Mapping of hydrogen production projects in Norway

Gassco has performed a mapping of large-scale hydrogen production initiatives in Norway that are relevant for potential hydrogen export to Germany. Currently, the most mature renewable hydrogen projects are small-scale and located in remote areas. The most mature large-scale projects identified are the Clean Hydrogen to Europe (CHE) project by Equinor, and the Aukra Hydrogen Hub (AHH) project being developed by a consortium of Shell, CapeOmega and Aker Horizons. These are in an early study phase, low-carbon hydrogen production projects, converting natural gas to hydrogen with CCS, and are aiming for a start-up in 2030. Hydrogen production quantities from the two projects are given in Table 4-1.

[8] (Johnson Matthey, 2022), (Pettersen, et al., 2022), (Bukkholm, et al., 2021)

Table 4-1 Production capacity (at 100% hydrogen purity and regularity)

Hydrogen production projects	Location	Production capacity 2030[9] Mtpa	Production capacity 2040 Mtpa
Aukra Hydrogen Hub (AHH)	Nyhamna	0.45	0.45 + 0.45[10]
Clean Hydrogen to Europe (CHE)	Kollsnes, Mongstad or Kårstø	0.45	up to 2.25

The AHH project is planned to be located at Nyhamna, close to the natural gas processing plant. The location for the CHE project is not yet decided, but will potentially be located in the Kollsnes, Mongstad or Kårstø area.

Several reports have been published showing the levelized cost of low-carbon hydrogen production (LCOH). The Department for Business, Energy & Industrial Strategy in the UK issued a report in August 2021[11] with detailed economic information on different technologies. An important conclusion in the report is that costs for natural gas and electricity constitute around 50% of total production costs, whereas the investment cost is around 25%.

Adjusted for relevant energy prices, the technical maturity, and the recent cost developments in the industry, the pre-tax LCOH could be estimated to be in the range of 70-110 EUR_{23}/MWh[12] excluding H_2 transport. For comparison, the current price of natural gas is around 35 EUR_{23}/MWh whereas the long-term price forecast used in the analysis is 25 EUR_{23}/MWh.

The unit cost for the Offshore hydrogen transport (H2T) study is described in section 5. The diagram below shows an illustration of a typical distribution of the cost elements for the H_2 value chain.

[9] Production capacity with a start-up in 2030 is ambitious considering the uncertainties related to the realization of the full value chain.
[10] Renewable hydrogen production capacity from mid-2030
[11] (Department for Business , 2021)
[12] Calculated based on UK report (Department for Business , 2021) and aligned with input from the industry

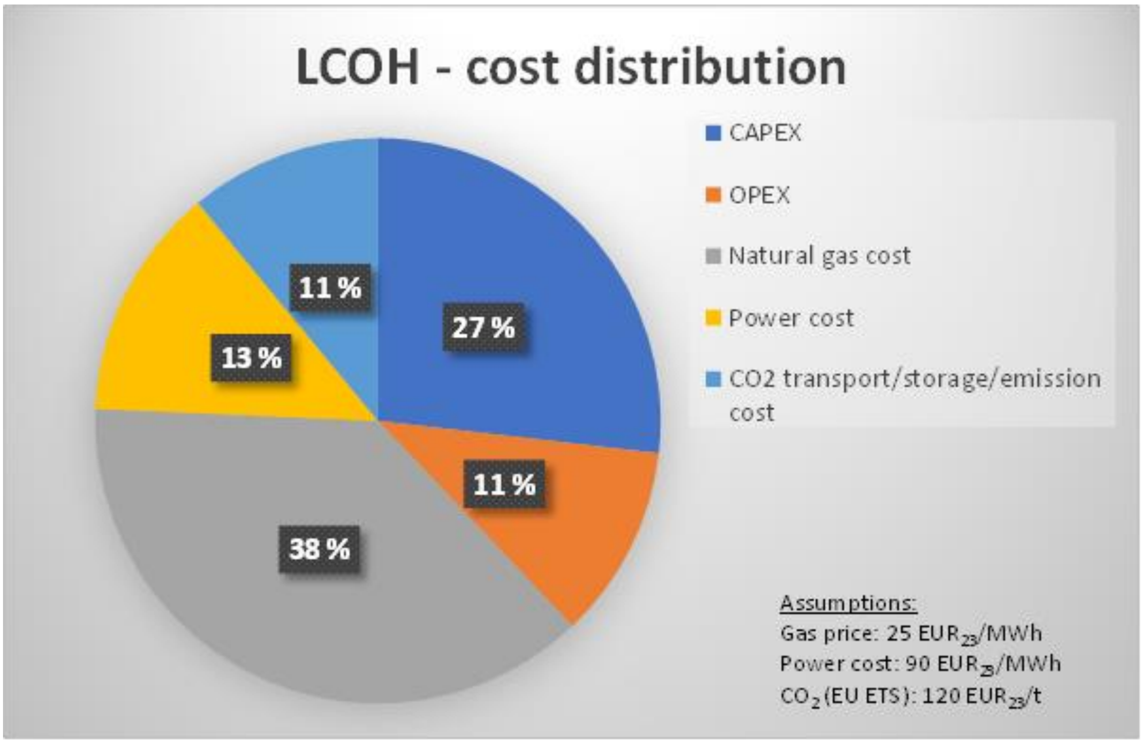

Figure 4-3 Cost distribution for hydrogen production

In addition to the CHE and AHH projects several renewable hydrogen projects are being considered. These are projects related to Norwegian offshore wind, Danish offshore wind and German offshore wind and a few Norwegian onshore initiatives. In Norway the offshore wind and onshore projects are less mature and smaller in scale. In the North Sea offshore wind is an industry being developed, with a large potential for power production. Offshore production of renewable hydrogen through electrolyser technology is being matured.

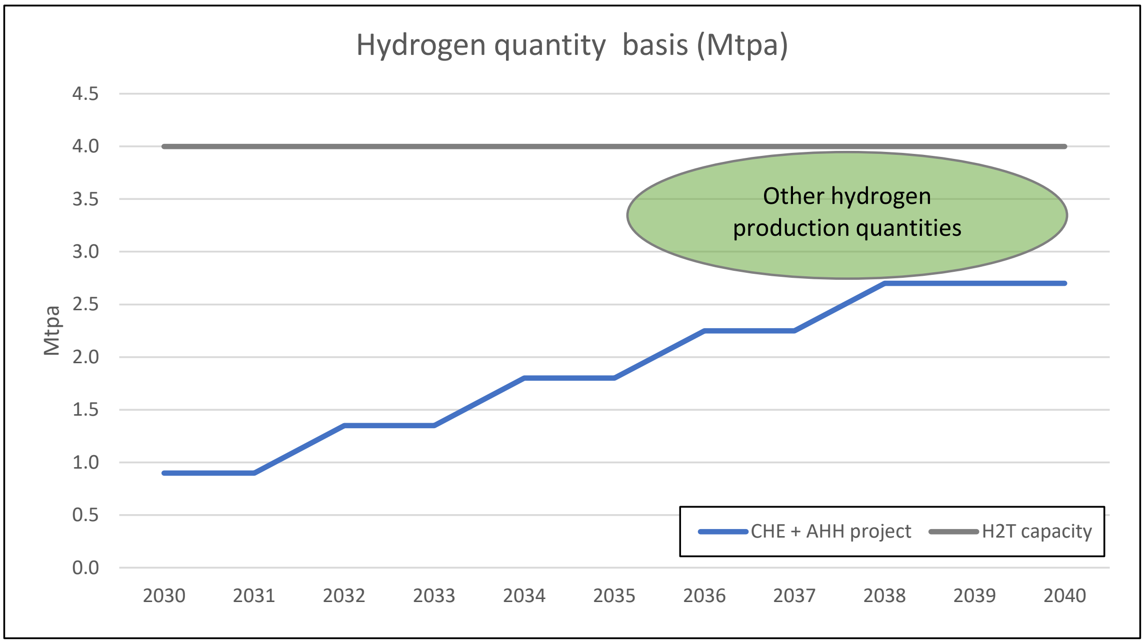

Figure 4-4 Hydrogen quantity basis

The figure above gives an overview of the potential hydrogen quantities from the projects and the potential for other hydrogen production quantities to be transported in the H2T infrastructure.

5 Offshore hydrogen pipeline from Norway to Germany

Gassco has on behalf of an industry sponsor group[13] performed a feasibility study of a hydrogen pipeline from Norway to Germany. In addition to the reuse and new pipeline scope of work, the study work includes landfalls, valve stations, tie-in options, receiving facilities including metering and gas monitoring in Germany.

Two main concepts have been evaluated, see figure below:

Concept 1:

- New 20" inch pipeline from Nyhamna to 40" pipeline sub-sea tie-in point (approximately 410 km to Kollsnes).
- New 40" inch pipeline from Kollsnes/Mongstad/Kårstø to a Europipe sub-sea tie-in point downstream of Draupner (approximately 315 km from Kollsnes).
- Reuse Europipe including landfall to Dornum.
- New hydrogen receiving terminal in the Dornum area.

Concept 2:

- New 20" inch pipeline from Nyhamna to 40" pipeline sub-sea tie-in point (approximately 410 km to Kollsnes).
- New 40" inch pipeline from Kollsnes/Mongstad/Kårstø to the Wilhelmshaven area (approximately 845 km from Kollsnes).
- New hydrogen receiving terminal in the Wilhelmshaven area.

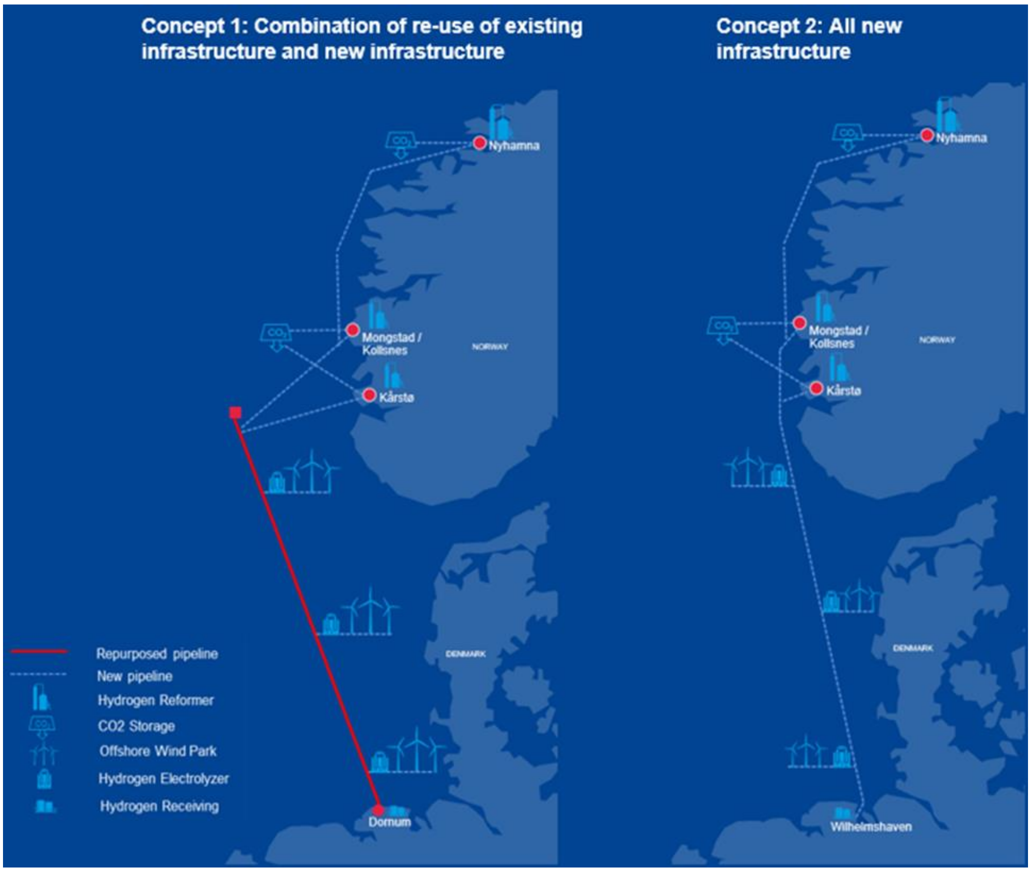

Figure 5-1: Offshore hydrogen transport concepts studied

[13] A/S Norske Shell, Aker Horizons, Equinor Energy AS, Energy AS, Hav Energy NCS Gas AS, Hydro Havrand, North Sea Infrastructure AS, CapeOmega AS, PGNiG Upstream Norway AS, Silex Gas Norway AS, TotalEnergies EP Norge AS, Vår Energi ASA and Wintershall Dea AS

The pipeline design has been based on the indicated production of low-carbon hydrogen from the AHH project (Nyhamna) and the CHE project (Kollsnes, Mongstad or Kårstø). In addition a 30% extra capacity has been added to account for other future projects, for instance offshore hydrogen renewable production. The total capacity is 4 Mtpa (14-18GW dependent on heating value and hydrogen purity). The capacity basis used in the feasibility study is subject to optimisation in the next study phase.

A hydrogen transport capacity of 4 Mtpa in Europipe is yet to be confirmed. This is subject to ongoing work with DNV, which needs to be concluded before the selection of concept if Concept 1 is to be selected for further maturing. The main uncertainty is related to the maximum operating pressure for hydrogen service, with respect to the technical integrity of the pipeline.

The reuse of Europipe for hydrogen transport is dependent on the need for gas transport flexibility and capacity. Based on the expected future need for gas export currently identified, reuse is possible around 2030. Such reuse will however reduce the total natural gas transport capacity to German delivery points by 20-25% and hence reduce the market flexibility and the opportunity for natural gas value creation.

A new receiving terminal in Germany is required in both transport concepts, as the reuse of the existing receiving terminal for natural gas has been evaluated as not feasible for hydrogen. For the Europipe reuse case (concept 1) the terminal location is assumed to be in Dornum close to the existing Europipe receiving terminal, and for a new pipeline to Germany (concept 2) the location is assumed to be in the Wilhelmshaven area.

A preliminary authority plan has been developed identifying the main regulatory bodies including required permitting processes. The permitting process related to installing a new hydrogen pipeline through the Wadden Sea area could be challenging and time-consuming. Early dialogue with German national and regional authorities has therefore been established. In this dialogue all pipeline projects with an interface to a potential new landfall(s) should be coordinated and aligned.

Cost estimates have been provided by the technical study providers Equinor and Shell and has been quality-assured by Gassco and benchmarked against the internal cost database. See Figure 5-2 below for expected CAPEX in billion EUR_{23}. OPEX has also been calculated and sums up to approximately 15 $MEUR_{23}$ per year. The accuracy of the cost estimates is according to Gassco feasibility decision gate requirements, which is +/- 50%. The unit capital cost is given in EUR_{23}/MWh and EUR_{23}/kg hydrogen and is based on total CAPEX and the sum of quantities shown in article 4.2 for a 25-years period using a discount rate of 7% pre-tax both on cost and quantities.

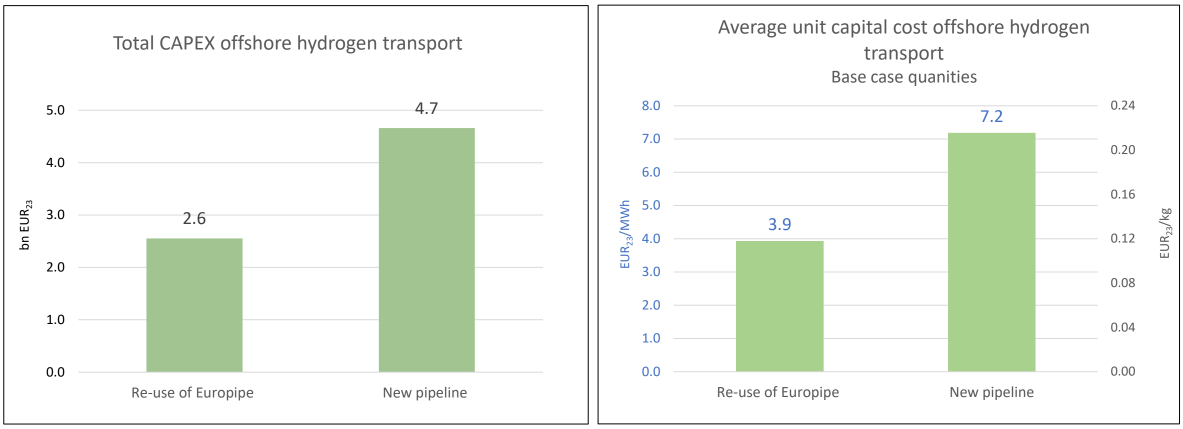

Figure 5-2 Total CAPEX and unit capital cost for the offshore hydrogen transport alternatives

Based on the assumptions given in the H2T study, the cost of offshore hydrogen transport constitutes a minor share of the total hydrogen value cost compared to the cost of Hydrogen production.

To be ready for a start-up in 2030, the main milestones for the H2T project should be as follows:
- Concept select decision: Q1 2025.
- Final investment decision: Q3 2026.
- Start-up: Q4 2030.

The H2T project schedule is ambitious considering the uncertainties related to the commercial maturity of the value chain, regulatory and commercial framework, technology qualification, permitting and long lead items procurement. Progress on these activities is needed to avoid a schedule delay.

Both the reuse of Europipe and the new pipeline to Germany concepts is recommended to be further matured in the next phase. The Europipe reuse concept indicates a significantly lower CAPEX than a new pipeline. A new pipeline can be designed to fit the German capacity and energy flexibility need, but comes with significant investment costs, increased pressure on the steel market and potentially an extensive permitting process for the Wadden Sea crossing and shore approach. A significant technology qualification scope will be relevant for both concepts but reuse of Europipe could be subject to more schedule delays.

There is a general lack of regulatory requirements, codes and standards for offshore transport of hydrogen. Work is ongoing to address this issue, but close dialogue with relevant stakeholders and authorities will be important in the way forward.

The technical maturity of the transport alternatives studied in the H2T feasibility study is considered sufficient to move forward to the next project phase. The H2T industry sponsor group approved the technical maturity of the H2T feasibility study to be sufficient to move forward to the next project phase. Before decidingto commence with concept selection studies, there are some follow-on activities that need to be further matured:

- Clarify the regulatory framework for hydrogen infrastructure as a basis for the composition of a possible investor group for offshore hydrogen infrastructure.
- Further optimise scope, schedule and budget for the next phase.
- Keep momentum on selected Technology Qualification Program (TQP)activities.
- Continue dialogue with German federal and regional authorities to clarify/optimise the permitting process.
- Explore opportunities and synergies with other ongoing hydrogen offshore infrastructure projects, e.g., the AquaDuctus project.

6 Onshore hydrogen transport network in Germany

FNB Gas is the association of supra-regional gas transmission companies (TSOs) in Germany, responsible for the network development plans for the natural gas transport pipeline network. They have also been actively working on the development of a hydrogen network in Germany. FNB Gas and its members supported dena as responsible for the work stream on Onshore Transport in Germany in the Joint Feasibility Study, with the aim of assessing the required grid expansions, and associated costs, to facilitate hydrogen import from Norway. As part of this work FNB Gas performed an updated system analysis of the hydrogen network development based on different flow situations and design cases for the possible receiving terminal locations indicated in the Gas Network Development Plan (NDP) 2022 – 2032.

6.1 Hydrogen Network Development

Transmission network operators and other potential hydrogen network operators submitted a plan for a hydrogen network in the framework of the Gas Network Development Plan 2022–2032. The determined hydrogen network of the hydrogen modelling is based on the reported requirements of a WEB market survey of hydrogen production and demand projects in Germany, identifying the need for hydrogen transport. It is also aligned with the results of the Gas Network Development Plan 2020–2032.

To exploit existing infrastructure potential as early as possible, the transmission system operators initiated several calls to invite other potential hydrogen network operators to actively participate in the modelling of a national hydrogen network. Pipeline network infrastructure operators were also encouraged to register existing and planned pipeline systems for the transport of hydrogen for consideration.

The result of the modelling is shown in Figure 6-1, illustrating the potential hydrogen network in Germany including production (Entry) and demand (Exit).

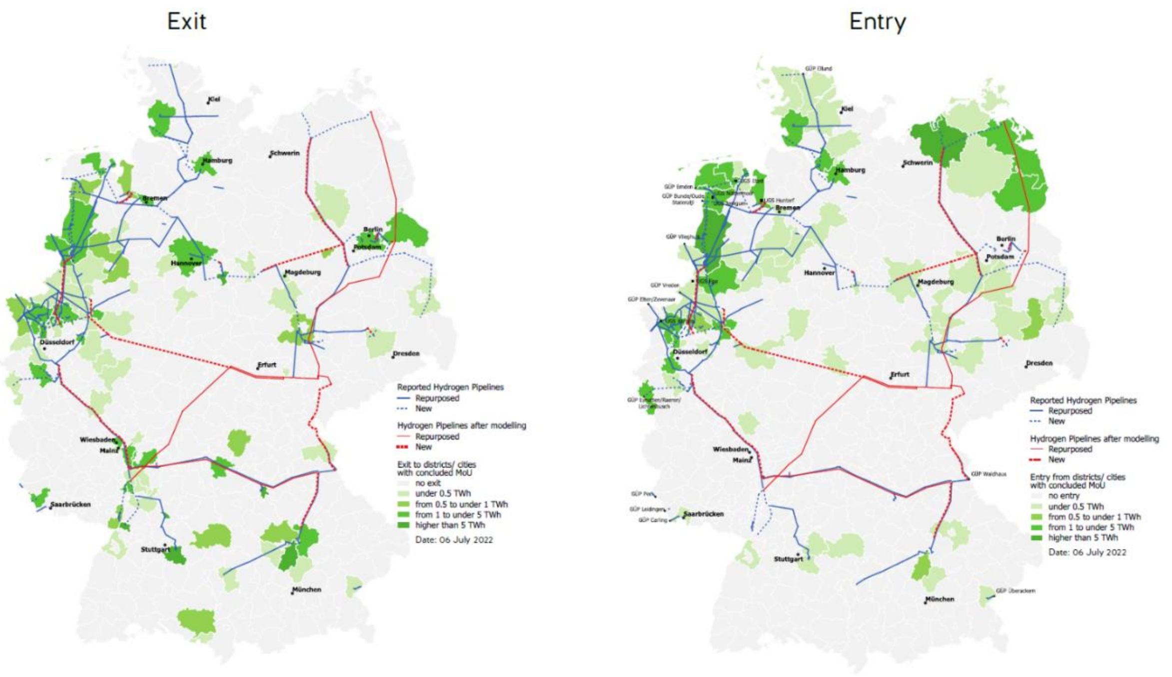

Figure 6-1: System Analysis of the German hydrogen network development in 2032 including entry (potential production sites) and exit points (potential consumers).

The accumulated investment costs of the hydrogen network resulting from the modelling is shown in Table 6-1, for the years up to 2027 and 2032. The costs up until 2032 are also shown in Figure 6-2 (NDP - orange).

Table 6-1: Result of the hydrogen modelling in NDP 2022-2032[14]

	Until end of 2027	Until end of 2032
Mainline compressor	0–25 MW	0–245 MW
Lead compressor	0 MW	0–100 MW
Pipelines	2,900–3,000 km	7,600–8,500 km
Investments	**EUR 2.3–2.8 billion**	**EUR 8.1–10.2 billion**

An important part of the onshore transport workstream has been to evaluate the possible locations of the receiving terminals for a hydrogen pipeline from Norway, as these serve as interface points to the onshore hydrogen pipeline system. This evaluation included two potential new locations in Wilhelmshaven and Brunsbüttel, as well as the existing locations in Dornum and Emden.

The analyses show that receiving terminals in Emden, Wilhelmshaven and Dornum require minor modifications to the NDP 2022-2032. In the case of a receiving terminal in Brunsbüttel the required additional investment was higher than in the other locations, but still lower than the maximum CAPEX calculated in the NDP. The CAPEX changes depend on various assumptions with receiving pressure being an essential one. One example of CAPEX of the German hydrogen network with a medium-high receiving pressure is shown in Figure 6-2. As shown, the costs are slightly higher for Brunsbüttel, but not significant enough to discard this option. There are further analyses to be performed as part of the Core Network development, which also would include imports from Norway.

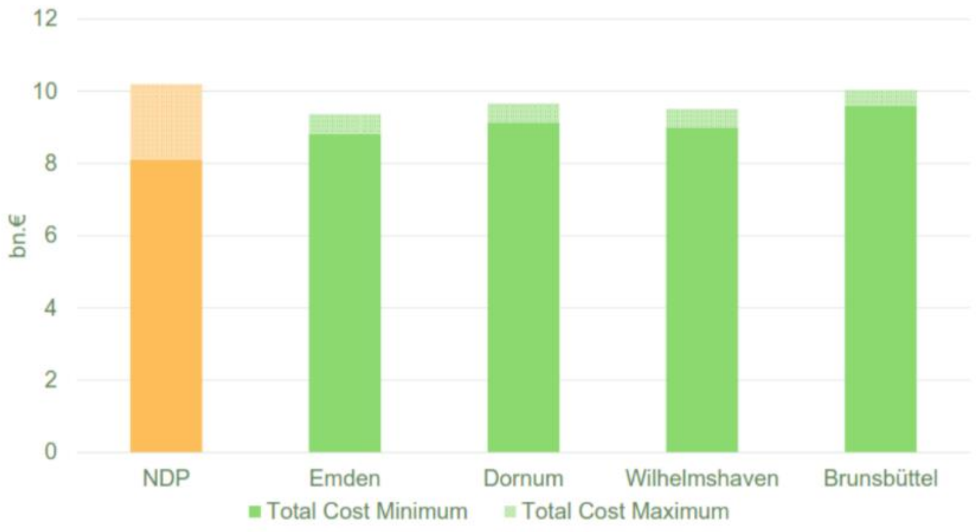

Figure 6-2: Comparison of CAPEX of the German hydrogen network for one pressure scenario with different landing points

The German TSOs are maturing individual pipeline projects according to the results of the NDP 2022-2032. These projects are shown in Figure 6-3 below. The project timelines for all the projects relevant to connecting to a hydrogen pipeline from Norway indicate that they could be ready for operation in time for start-up in 2030.

[14] (FNB Gas, 2023)

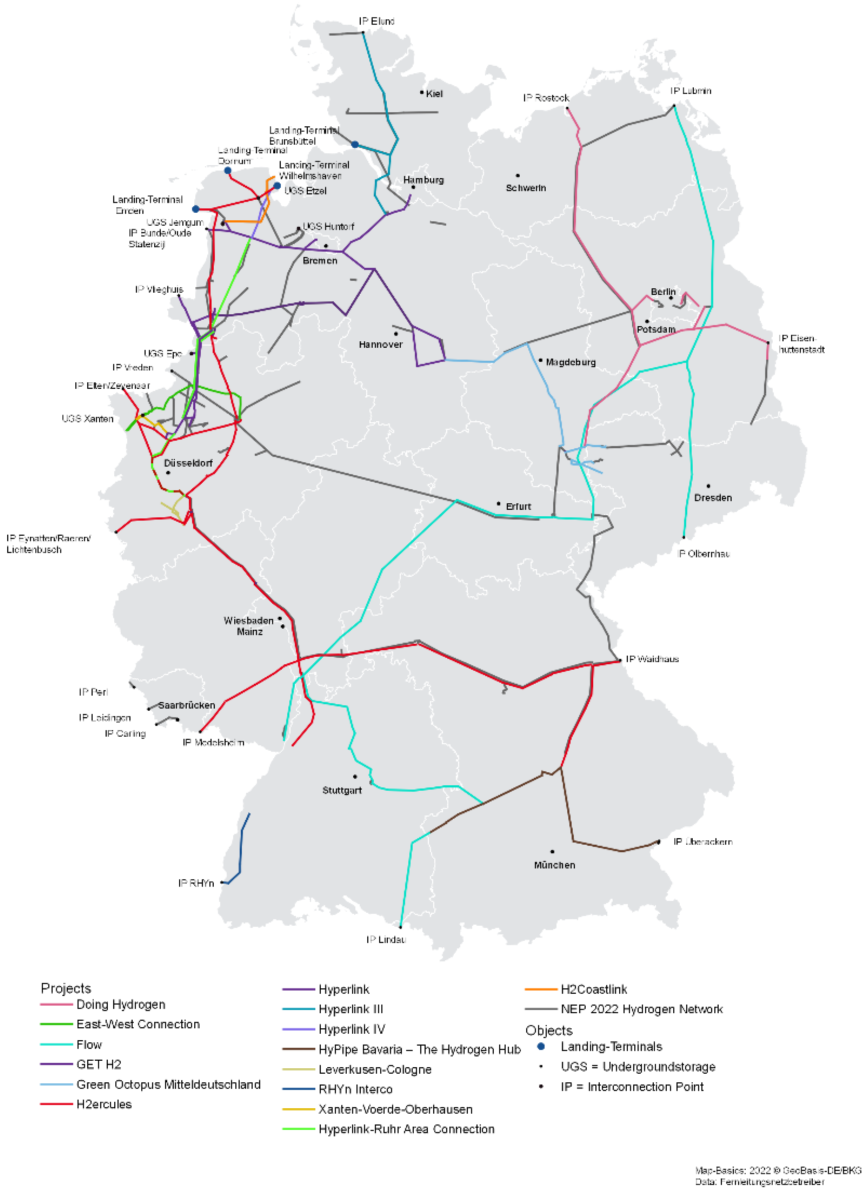

Figure 6-3 Project overview for the German hydrogen network

6.2 Hydrogen Core Network in Germany

In May 2023, the German Federal Government published the amendment of the Energy Industry Act (Energiewirtschaftsgesetz – EnWG-E), which provides the legal and regulatory framework for the hydrogen infrastructure. The amendment of the Energy Industry Act, aiming for completion of the parliamentary procedure end of 2023, will mandate the Association of the German gas TSOs (FNB Gas) to submit a plan for the realization of a hydrogen core network by 2032. The core hydrogen network will connect central hydrogen locations throughout Germany. It will provide essential infrastructures, to be put into operation by 2032. The plan for its development is to be examined and approved by the German Federal Network Agency.

On November 15th, 2023 the transmission system operators published their optimised modelling for a supra-regional hydrogen core network by 2032. The draft (shown in Figure 6-4will be conusulted by stakelholders until the 8th of January. Figure 6-4

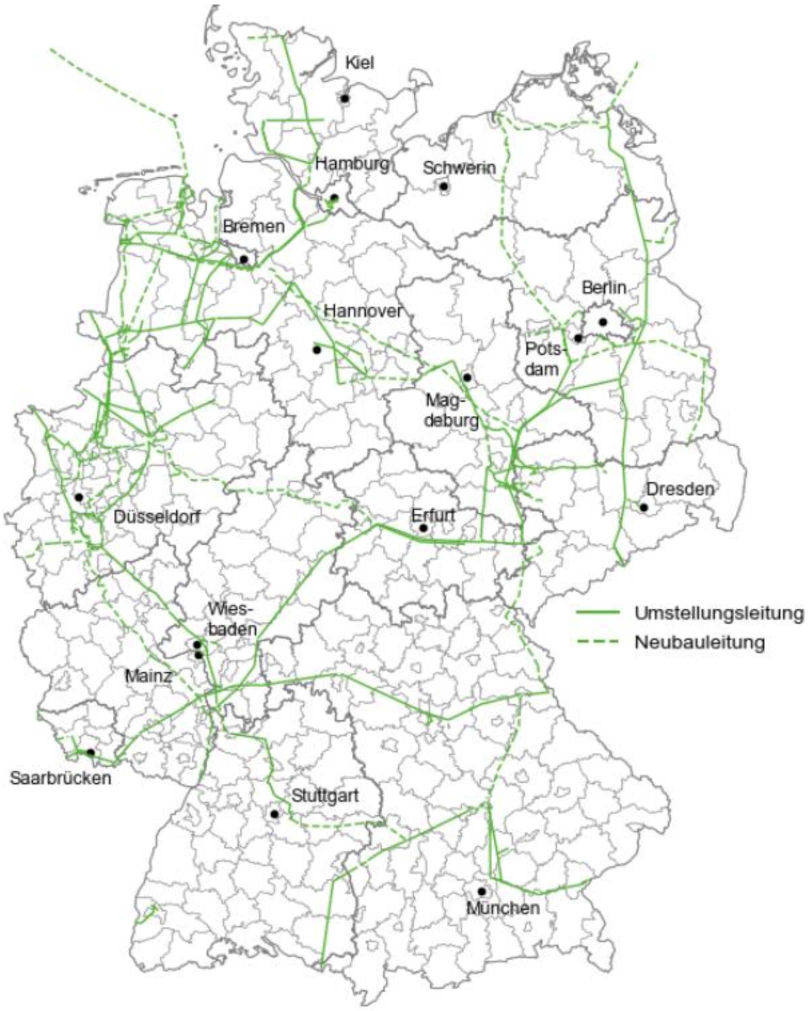

Figure 6-4: Draft map of the Hydrogen Core Network in Germany

The hydrogen core network aims to have a total pipeline length of 9,721 km, with approximately 60% based on the conversion of existing natural gas pipelines. In addition to having connection points for pipeline imports the network is designed for imports via ships, converting hydrogen from derivatives such as ammonia and liquid organic hydrogen carriers (LOHC).

Compared to the hydrogen network considered in the Onshore Transport Working Group, the Aquaductus project has been included in the German Core Network. This is an offshore pipeline planned to transport domestically produced hydrogen from offshore wind farms in the German exclusive economic zone. There could be potential synergies between this project and the H2T project that will be investigated in the next phase.

Due to high investment costs of roughly 19.8 billion euro and initially low numbers of connected users, as well as smaller hydrogen quantities, financing through network tariffs would result in prohibitively high transport costs. To ensure rapid and efficient network development and a fair distribution of costs and risks, the German government is working on a uniform hydrogen network tariff during the market ramp-up and considering a concept of intertemporal smoothing of the tariff ("amortization account") backed by a subsidiary state guarantee.

The core-grid is designed for a much larger hydrogen market than the hydrogen grid from the NDP 2022. Therefore, the integration of the Norwegian volumes will be still valid.

7 Hydrogen consumption and storage in Germany

The expected increase in hydrogen demand in Germany has been reflected in a range of studies based on scientific modelling, as well as in political targets. The demand forecasts for 2030 have a very wide range, which is partly very clearly below the political targets and partly clearly above them. All scenarios assume that Germany will need to import hydrogen and synthetic energy carriers. The update of the National Hydrogen Strategy expects an import quota of 50% to 70% of the German demand in 2030. In the following years up to 2045, the federal government even expects this quota to increase even further.

As part of this feasibility study, dena has backed up the existing scientific and industry scenarios with specific figures from the companies in order to check the reliability of the calculated ranges.

7.1 System-based demand scenarios

The German National Hydrogen Council (Nationaler Wasserstoffrat - NWR) published a white paper in February 2023 showing projects with a total hydrogen demand (incl. unabated fossil hydrogen[15]) of 92 - 129 TWh in 2030 and 964-1364 TWh between the years 2040 and 2050[1], which are shown in Figure 7-1. The demands are based on information provided by the sectors from the process industry, traffic and transport sector and heating market. The data was subsequently checked for plausibility by the NWR. The NWR is appointed by the German government as an independent, non-partisan advisory board, which consists of 25 high-ranking experts in the fields of economy, science and civil society. Although some uncertainty is associated with these data, the analysis provides a rough but valid overview of expected quantities that will have to be produced domestically or imported to Germany. For 2030 alone, the NWR expects a demand for low-carbon and renewable hydrogen of 56 to 93 TWh, the majority of which is for the steel industry and heavy-duty transport.

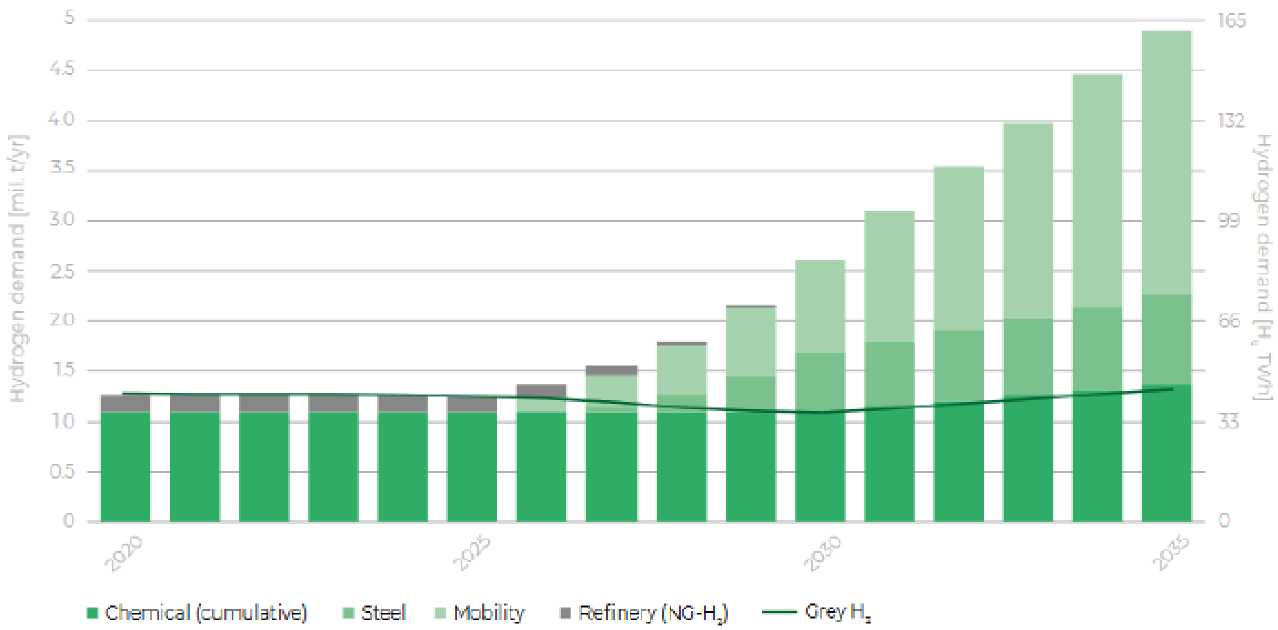

Figure 7-1 Hydrogen demand in various sectors (excluding heating) by 2035

[15] Also referred to as grey hydrogen

In all major scenarios and political targets, the hydrogen demand in Germany in 2030 exceeds the expected import volumes from Norway. In only a few cases it is assumed that German requirements consist mainly of liquid energy carriers, which would be imported by ship. In this case, the pipeline-bound hydrogen import from Norway would exceed German demand. In 2040, the demand exceeds the imports from Norway in all cases, despite the continued wide ranges. In the update of the German hydrogen strategy, demand is expected to reach 95 to 130 TWh in 2030, corresponding to approximately 3-4 Mtpa.

7.2 Project-based demand development

As part of the work stream on storage and consumption in Germany, dena has done a mapping of related industrial projects. The observation is that more and more projects are appearing, and a sample of relevant projects is shown in the figure below. Dena has identified companies and projects within the industry, storage and energy sector that indicated a possible hydrogen demand that is above 1TWh/a in 2030 in the market survey by FNB Gas and therefore will likely be connected to the pipeline projects selected in the Onshore Transport Working Group in 2030. After the identification, bilateral discussions were arranged to assess the eligibility and condition of participation in the working group for each company.

One important output of the cooperation within the working group is comprehensive project profiles, which deliver information about the specific hydrogen projects. Relevant information included is amongst others expected demand, demand curve, start and ramp-up of consumption, the maturity level/status of the projects, requirements on the colour and source of hydrogen, as well as import and supply intentions.

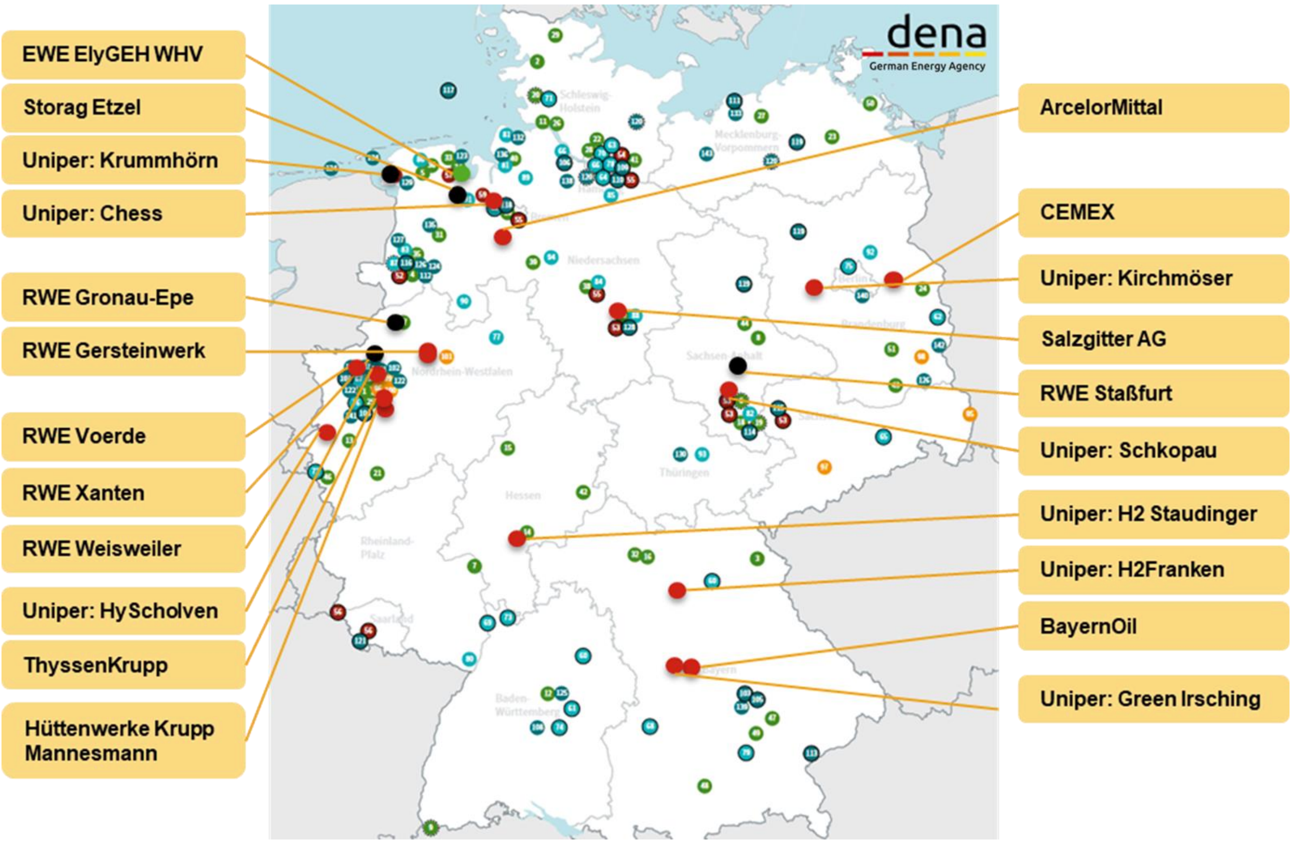

Figure 7-2: German industry projects on hydrogen consumption and storage; the boxes next to the map show the projects included in the working group (red = hydrogen consumption projects, black = hydrogen storage projects[16]

A total of 23 projects were evaluated in the Working Group for Storage and Consumption, of which 17 projects use hydrogen as an energy carrier in an application and 6 projects are cavern storage projects. The consumption projects come from four different sectors: steel industry, energy industry, cement production and refinery industry.

Hydrogen consumption in Germany will already start to increase before 2030. The projects of the Working Group for Storage and Consumption mainly represent the first movers, some will already start switching to hydrogen as early as 2024.

The cumulative demand of the projects (see Figure below) is about half of the German assumptions of the Federal Ministry for Economic Affairs and Climate Action (BMWK) and the NWR. Assuming imports from Norway would amount to about one million tonnes per year (~30 TWh) in 2030, the German demand would exceed this significantly, even though only a selection was represented in the working group.

[16] *Source map: https://h2-dialog.info/fileadmin/H2_Dialog/Dokumente/230413_dena_GR_Wasserstoffprojekte_Deutschland_WEB.pdf*

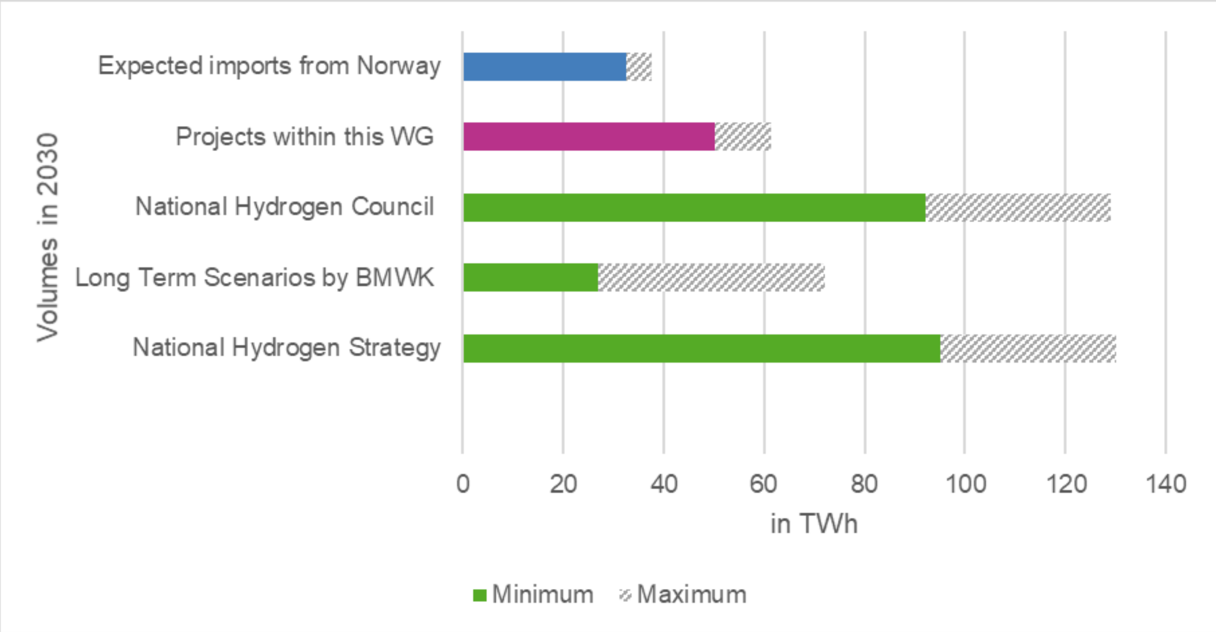

Figure 7-3 Hydrogen demand in 2030 in Germany based on different scenarios, political targets and on the projects of the Working Group in comparison to the expected imports from Norway

The demand profile of the consumption projects has different supply curve requirements. Some require a steady inflow throughout the year, while others expect a significantly volatile demand profile. To balance the fluctuations in demand and the supply of renewable hydrogen from electrolysis, working group members stated that Germany will have a considerable hydrogen storage need.

The announced storage volumes will probably not be enough to cover German demand. However, in the first few years it is assumed that the ability of the storage technology to quickly switch between injection and withdrawal is more important than the pure quantitative capacity. With increasing overall demand for hydrogen in the energy system and new customers, who have a seasonally changing demand curve, it is assumed that more storage projects will be developed. Germany has large cavern storage potential, some of which is currently used for natural gas or oil. The current status of the investigation suggests that reusing these caverns is technically feasible through technical developments in storage system technology. In the update of the national hydrogen strategy, the German government has announced that it will present a concept for hydrogen storage so that further projects can be developed. In the first half of 2024, the important questions are to be clarified in cooperation with FNB Gas and the Federal Network Agency. Further projects are therefore in the very early stages of development but could be further matured based on the expected new regulatory framework.

7.3 German hydrogen strategy update

Shortly after the completion of the preparation of the results for the two German working groups, the update of the National Hydrogen Strategy (NHS 2023) was adopted by the Federal Government on 26.07.23. The central objective is to accelerate the market ramp-up of hydrogen. The NHS 2023 specifies four fields of action for the year 2030, which are to be underpinned by various short- to medium-term tasks and measures:

1. Ensuring sufficient availability of hydrogen and its derivatives:
   - The expansion target for electrolysis capacities will be raised from 5 GW to at least 10 GW by 2030. An important component is the availability and provision of sufficient renewable

electricity, which is converted into renewable hydrogen by means of electrolysis, as well as support programmes for electrolysers.

- Considerable import of renewable and, at least also in the market ramp-up phase, low-carbon hydrogen is necessary to cover demand. The publication of an import strategy is planned for the end of 2023.

2. Expansion, financing and regulation of the hydrogen infrastructure (also import infrastructure) in view of high investment costs and initially low consumer base: On 24 May 2023, the Federal Cabinet decided on an amendment to the Energy Industry Act (EnWG) for this purpose to create a legal basis for a hydrogen core network.
3. Establishment of hydrogen applications: By 2030, hydrogen will particularly be used for applications in industry, heavy commercial vehicles and increasingly in aviation and shipping. The NHS 2023 makes no restrictions on the use of hydrogen in the individual fields of application. In the electricity sector, hydrogen contributes to energy supply security through gas power plants that can be repurposed with climate-neutral gases (H_2-ready) and through installation of system-serving electrolysers.
4. The creation of effective framework conditions to accelerate the market ramp-up of hydrogen through simplified approval procedures, clear standards, funding of research and development as well as a targeted build-up of skilled workforce.

The update also contains passages that refer specifically to the cooperation between Germany and Norway and describes the more recent position on the use of low-carbon hydrogen in Germany, which will be provided via imports.

8 Technical safety and technology development

The different properties of hydrogen compared to natural gas will result in changes and new uncertainties. Some of these properties impact safety, while others impact the design and operation of production facilities, and pipeline systems as well as the usage on the consumer end.

The small hydrogen atoms can diffuse into steel materials, causing Hydrogen Embrittlement (HE). This can result in loss of mechanical ductility, reduced fracture toughness, and degradation of fatigue properties. Hydrogen atoms may also absorb into non-metallic materials such as polymers and cause blistering, cracking, dimensional changes, and potentially result in failure and leakages.

Hydrogen carries about 30% of the energy per volume compared to natural gas and the density is also much lower, around 12% of natural gas. Thus, to meet the current energy transport capacity requirements when converting from natural gas to hydrogen, larger gas throughput volumes and consequently gas flow velocities are needed, and three times larger gas volume needs to be compressed. The capacity to store hydrogen in pipelines (line-packing) is 30% lower than for natural gas. Preliminary investigations indicate that pressure cycling reduces the fatigue lifetime of the pipeline when operating with hydrogen, which again impacts operational flexibility and line-packing.

Due to the much lower molecular weight of hydrogen compared to natural gas, the speed of sound is high, close to that of liquids. This may impact the operational philosophy of pipelines and the design of pressure safety systems.

Technical safety is also an important aspect for hydrogen. The specific properties of hydrogen differ substantially from those of natural gas and conventional oil and gas products. The main differences are related to a larger flammability range, lower ignition energy and higher laminar burning velocity, leading to an increased possibility of high explosion pressures or detonation if hydrogen releases accumulate in enclosed or congested areas. Taking hydrogen’s specific characteristics into consideration in design and operation is vital to ensure safe conditions.

A comprehensive assessment of technology readiness is part of the project maturing across the value chain, including testing to close knowledge gaps. In the H2T project this has been carried out as a cooperation between Gassco and Equinor, while onshore transport in Germany has been assessed by DVGW and the TSOs.[17] So far, no technical showstoppers have been identified. However, especially for offshore transport, comprehensive technology qualification, involving many disciplines, is required to reduce risks and mature technologies going forward. This includes qualification of important components, such as gas quality and flow meters, compressors and valves, but also increasing the accuracy of process and flow modelling tools, gas detectors as well as leak frequency and ignition probability models. An interdisciplinary approach will be important in this work. In-line inspection tools (ILI) for the detection and monitoring of cracks in the pipeline walls, especially in the welds, may also be needed. ILI tool technology with the required sensitivity, and which can operate in a hydrogen environment, is not available today. A close dialogue and cooperation with vendors have been established to develop it in time for 2030.

[17] (Steiner, et al., 2023)

9 Risks and opportunities

To assess the feasibility of the production, transportation and application of hydrogen from Norway to Germany, it is necessary to comprehensively understand what risks and opportunities exist in the implementation of the value chain. The risks and opportunities throughout the value chain may be considered and evaluated differently between the different stakeholders. A selection of the main risks and opportunities throughout the value chain is described below.

Risks

The work performed in the joint feasibility study throughout the value chain indicates that the implementation of the entire market ramp-up comes with substantial risk. Especially there is risk connected to the economic viability of separate projects and building blocks of the value chain.

Further value chain misalignment, e.g., dependencies towards the other work streams in the value chain from production, transport, and storage to consumption would cause a schedule delay. The risk of misalignment between cost of product and willingness to pay, as well as the ability to commit to long-term supply and demand would introduce additional uncertainty in the decision process and could cause project development delays.

The regulatory framework for cross-border offshore hydrogen pipelines needs to be developed in due time before the planned investment decisions.

The pace of developing technical and regulatory codes, standards and guidelines for hydrogen pipelines and equipment could have a negative impact on the project schedule and cost. There is a risk related to the TQP impact based on technology immaturity creating uncertainty for the project schedule and cost.

Environmental, cost and schedule impact related to the German nearshore/landfalls and corresponding authority process is a risk for the new offshore pipeline concept, due to the crossing of the nature sensitive Wadden Sea area.

The financing model for the hydrogen core grid in Germany is to be finalised by the end of 2023. Any delays in this process will have a significant impact on the timeline of maturing the onshore transport projects, and in turn. establishing the hydrogen value chain.

The use of hydrogen in the consumer projects is considered to still be at the early phases of the ramp-up. But due to the ambitious goals, however, technical developments must now be brought into use in just a few years, for which similar developments in the past sometimes took decades. The serious risks therefore relate primarily to delays in funding procedures, approval processes, but also to the construction of an onshore hydrogen network that would enable the supply of hydrogen in sufficient quantities in the first place.

Opportunities

Repurposing of existing gas infrastructure in a transition scenario from natural gas to low-carbon and renewable hydrogen would reduce the CAPEX substantially for the offshore infrastructure. This will contribute to reduce the risk of misalignment between cost of product and willingness to pay. The large-scale production and consumption approach in maturing the value chain and establishing the hydrogen market will contribute to further reduce this risk by decreasing the unit cost of hydrogen.

Support schemes such as IPCEI, and the framework for PCI/PMI would give an opportunity to seek public funding and optimise permitting processes. Also the German Core Network initiative is positive in reducing the risk of establishing hydrogen large-scale hydrogen transport capacity in Germany.

Exploring the potential synergies between the German-Norwegian offshore hydrogen pipeline and other infrastructure projects, e.g., the AquaDuctus project could lead to complementary effects and increase the robustness of both businesses cases.

The companies and projects in Germany expect advantages from the announced political support measures, such as the carbon contracts for difference, rising carbon and ETS prices, an electricity price cap for energy-intensive companies or further sector-specific subsidies.

It would be a schedule risk-reducing and CAPEX opportunity to align the value chain master schedule for procurement strategies regarding linepipe materials and long lead items.

Regarding considerations related to crossing the nature sensitive Wadden Sea area there is an opportunity to explore the synergies with both a CO_2 value chain and other planned pipeline projects.

10 Observations and key results

An overview of the main results and observations from work performed as part of the German-Norwegian joint feasibility study for the hydrogen value chain is summarised below. The value chain elements are reflected in the beginning, followed by the more specific elements related to the main building blocks of the value chain.

- Norwegian hydrogen could play a key role in the energy transition and on the path to greenhouse gas neutrality in Germany and Europe.
- The energy price for hydrogen will have to significantly exceed the energy price for natural gas to justify investments in a hydrogen value chain and the energy loss from hydrogen production.
- An integrated large-scale hydrogen pipeline infrastructure accommodates for reduced marginal cost of transport in a hydrogen value chain.
- Commercial commitments are needed to justify the development of large-scale hydrogen production and associated infrastructure.
- Significant investments are needed to establish a hydrogen value chain. This includes high investments in the hydrogen transport infrastructure although the cost of transport is relatively low compared to the cost of production.
- Long-term contracts for hydrogen energy and/or incentive schemes (e.g., Carbon Contracts for Difference (CCfDs), Important Projects of Common European Interest (IPCEI), and Projects of Mutual Interest (PMI)) would contribute to reduce the misalignment between cost of product and market price of renewable and low-carbon energy.
- Also, the German Core Network initiative is positive in reducing the risk of establishing hydrogen large-scale hydrogen transport capacity in Germany.
- Commitment from the industry and governmental support will be necessary with regard to product acceptance, permitting and regulatory framework.
- The updated National Hydrogen Strategy (NHS 2023) adopted by the German Federal Government, accommodates accelerated market ramp-up of hydrogen and includes the statement of the importance and possible use of low-carbon hydrogen.

Hydrogen low-carbon production

- Planned Norwegian projects could accommodate large low-carbon hydrogen quantities delivered at steady flow to Germany.
- The expected gas volumes from the Norwegian Continental Shelf are sufficient to accommodate large-scale low-carbon hydrogen production and export.
- Production of low-carbon hydrogen from natural gas will reduce energy export from the Norwegian Continental Shelf due to energy loss. When converting natural gas to hydrogen the energy loss is in the range of 20-30% including gas and power consumption.
- The pace of technology development and qualification together with developing technical and regulatory codes, standards and guidelines is important to reduce costs and keep a schedule towards 2030.

Hydrogen Offshore Transport

- The transport of hydrogen from Norway to Germany is considered technically feasible by 2030.
- The total transport capacity of the hydrogen offshore pipeline is 4 Mtpa, of which 2.75 Mtpa is low-carbon hydrogen from the Norwegian large-scale low-carbon hydrogen production projects. The remaining capacity is to account for future projects and tie-in volumes.
- The reuse of Europipe for hydrogen transport is dependent on the need for gas export. Based on the expected future need for gas export, reuse is possible in 2030. Further a reuse would reduce the CAPEX and average unit capital for offshore hydrogen transport. Such reuse will however reduce the total natural gas transport capacity to German delivery points by 20-25% and hence reduce the market flexibility and the opportunity for natural gas value creation.

- The regulatory framework for cross-border offshore hydrogen pipelines should be matured in the next phase to support the establishment of a commercial framework for an investment decision.
- Environmental Impact Assessments for the German nearshore/landfalls and corresponding authority dialogue and process (new pipeline) should be initiated early due to the crossing of the nature sensitive Wadden Sea area.
- Synergies with both a CO_2 value chain and other planned pipeline projects regarding the crossing of the nature sensitive Wadden Sea area have been identified.

Hydrogen Onshore Transport

- Modelling results from the joint work of the TSOs within FNB Gas show that the integration of imports from Norway is possible without significant cost increases for the entire system.
- Planning of the onshore transport system is already progressing well. German TSOs have been working on hydrogen network development and are involved in various infrastructure projects.
- The German TSOs propose a fast-track process for developing the first Germany-wide hydrogen network, seeking stable and reliable legal and regulatory framework conditions to enable infrastructure development and investment decisions.
- The regulatory framework for the hydrogen grid is currently being finalised. Investment decisions can thus be made in a timely manner.

Hydrogen Consumption and Storage

- The expected increase in hydrogen demand in Germany is reflected in scientific modelling and studies by associations and companies as well as in political targets. The demand level forecasts vary significantly, from clearly below to clearly above the political targets.
- As only parts of the hydrogen demand can be covered by German domestic production, large quantities of the demand will have to be covered by imports. The National Hydrogen Strategy states that 50-70% of the demand in 2030 will be imported, and the share could be increasing thereafter. The hydrogen demand forecast for Germany is significantly higher than the expected import volumes from Norway in 2030 as well as in 2040.
- Even though these demand scenarios are associated with uncertainty, the customers in Germany assume that it will hardly be possible to cover the demand with renewable hydrogen at the beginning of the market ramp-up. As such, the purchase of low-carbon hydrogen is expected to be necessary and therefore desirable.
- Hydrogen consumption in Germany will already start to increase before 2030. The projects of the Working Group for Storage and Consumption mainly represent the first movers, some will already start switching to hydrogen as early as 2024.
- Based on the existing storage projects in the planning there is an indication of shortage of storage capacity in the early years.
- Germany will have a large storage requirement, especially to compensate for the fluctuation of electrolyser outputs. Storage projects are already under development and the first demonstration projects are being implemented. More projects are expected to be initiated as the demand for storage increases.

There are several dependencies in the way forward of maturing the hydrogen value chain. The main one would be maturing the security of supply and demand, which would set the master schedule of the large-scale hydrogen producers. This could be the guideline for when the hydrogen transport infrastructure is required to be ready for operation.

For the next steps to further mature the onshore transport projects, the core network must be approved and the grants under the IPCEI framework have to be disbursed. Both steps are expected within this year. These are prerequisites for many of the final investment decisions that TSOs in Germany want to make.

Regarding consumption and storage projects, some final investment decisions have already been made for the first project stages. Further mapping, monitoring and inclusion of consumer projects are envisioned.

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