Use of hydrogen in pipelines in Europe

Literature study

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1 Introduction

This literature study related to the use of hydrogen in pipelines in Europe is part of the *European Partnership on Metrology* Project 21GRD05 Met4H2 Metrology for the hydrogen supply chain. This study focuses on the gas distribution grids, as well as any specific plans to use the grid to transport hydrogen in the form of gas at larger flow rates. The study also focused on relevant fiscal metering points and the demands for flow measurement technology. Outputs from 16NRM06 NEWGASMET and 20IND10 DECARB were included in the literature study.

2 Known, used and planned hydrogen distribution grids in Europe

2.1 Belgium

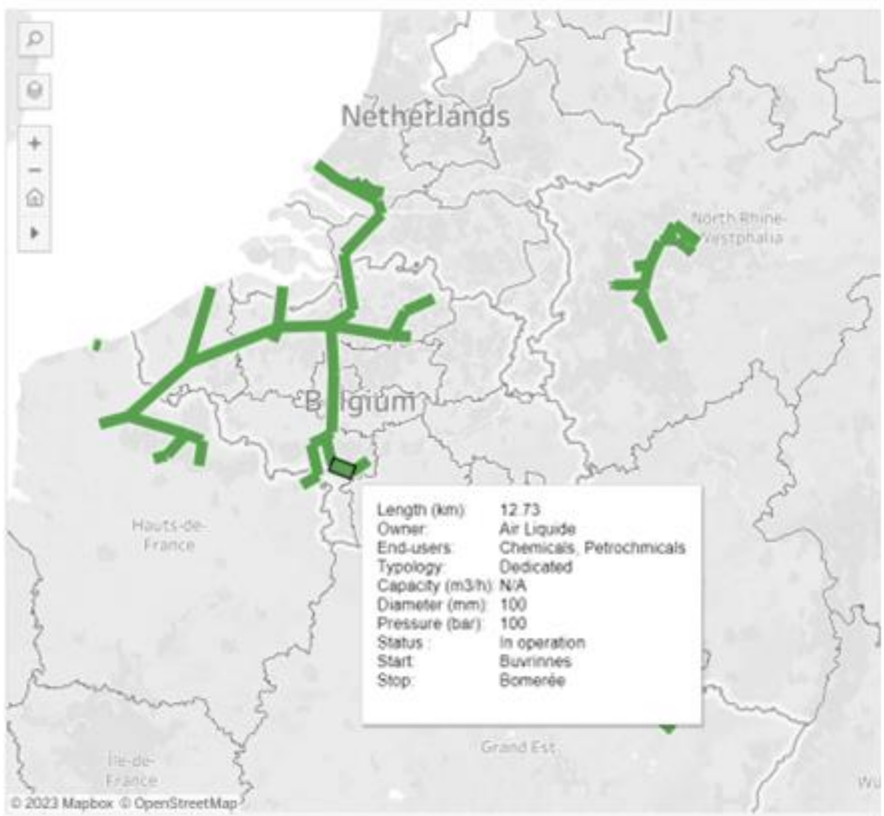

Figure 1: Hydrogen distribution networks located in Belgium

The website https://observatory.clean-hydrogen.europa.eu/ shows that the hydrogen distribution networks in Europe are mainly located in Belgium (Figure 1). The owner of these networks is the company Air Liquide [1]. In Belgium, the network is 964 km long and the end users are chemical and petrochemical companies.

2.2 Germany

The website https://observatory.clean-hydrogen.europa.eu/ shows that some others hydrogen distribution networks in Europe are located in Germany (Figure 2). The owners of these networks are companies Linde and Air Liquide [1]. In Germany, the network is 257 km long and the end users are chemical and petrochemical companies.

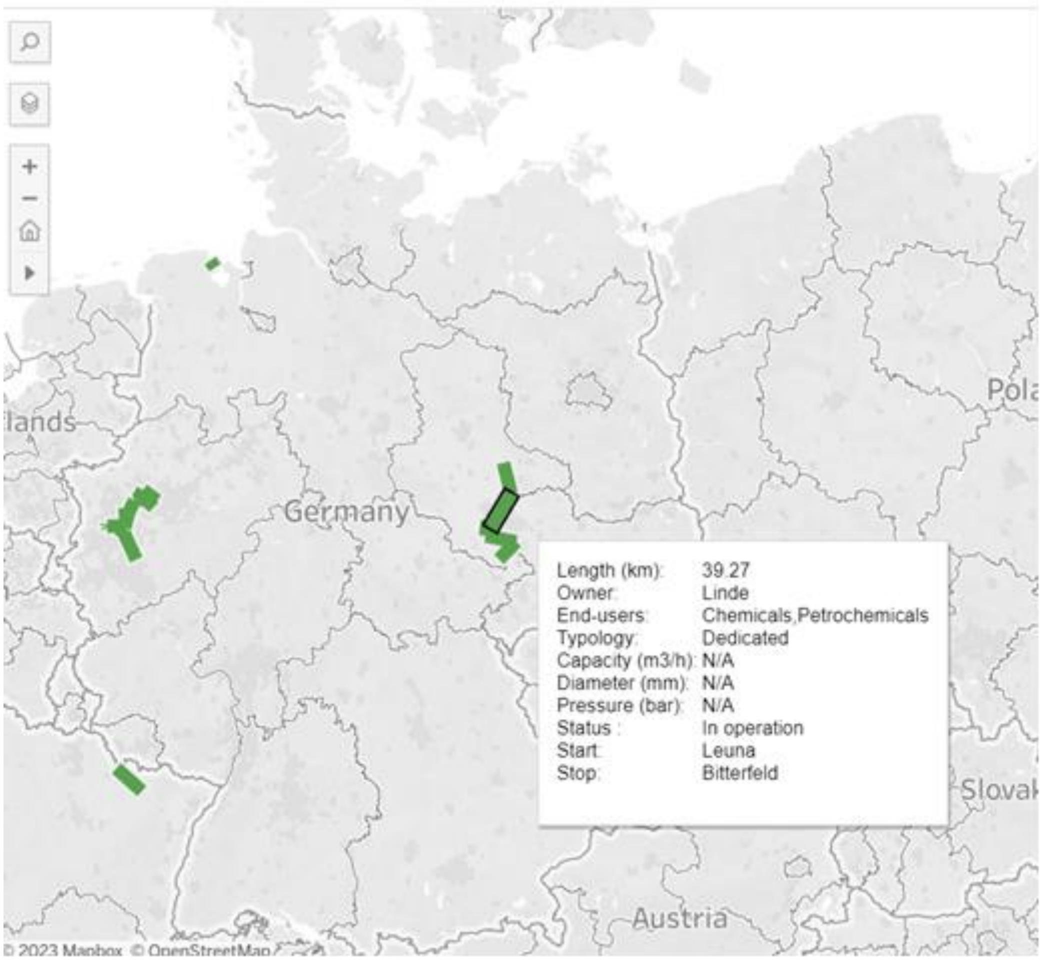

Figure 2: Hydrogen distribution networks located in Germany

The economic development organisations of the northern German states of Bremen, Hamburg, Mecklenburg-Vorpommern, Niedersachsen and Schleswig-Holstein have joined forces to form the green hydrogen initiative HY-5 [2] (Figure 3). The new initiative aims to make Northern Germany the strongest European region for green hydrogen in a near future and to develop and complete the value chain for green hydrogen.

Figure 3: Initiative HY-5 in Germany

2.3 France

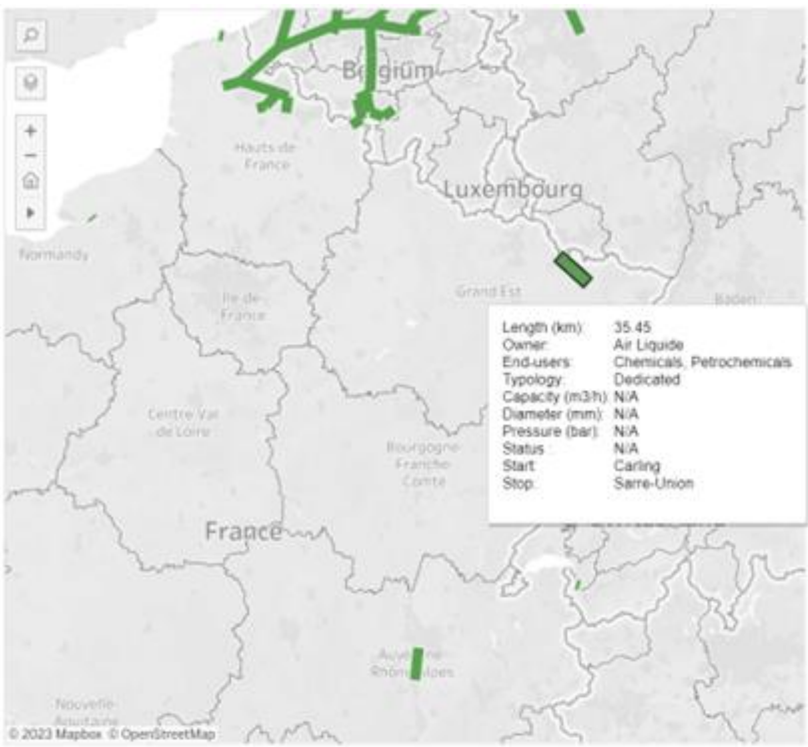

Figure 4: Hydrogen distribution networks located in France

The website https://observatory.clean-hydrogen.europa.eu/ shows other hydrogen distribution networks in Europe located in France (Figure 4). The owner of these networks is the company Air

Liquide [1]. In France, the network is 215 km long and the end users are chemical and petrochemical companies.

2.4 Netherlands

There is already a high-pressure pipeline (12 km) going from Dow Benelux to Yara. The hydrogen is a byproduct of Dow, used as feedstock at Yara. Companies Air Liquide and Air Products also operate hydrogen pipelines in the southwest of the Netherlands [1].

In many countries, discussions are only about mixing hydrogen in natural gas. This is not the case for the Netherlands. “Pure” hydrogen (>98 %) grids are expected here.

2.4.1 Distribution System Operators (DSO) grids and domestic hydrogen in the Netherlands

There is unfortunately no specification about use of gas meters in these projects. It can be supposed that some DSOs use existing domestic gas meters, typically diaphragm meters.

In the city of *Lochem* [3], there are 12 houses being fed with hydrogen as of December 2022. Tests will last 3 years. Houses got new boilers to run on hydrogen. The hydrogen is delivered using tube trailers but sent to the houses using existing grid pipelines.

Plans for a couple of hundred houses and DSO grid on hydrogen are mentioned here for the cities *Stad aan 't Haringvliet* [4] and *Rozenburg* [5]. In *Rozenburg,* two hydrogen boilers were installed in an apartment complex.

2.4.2 Transmission System Operator (TSO) in the Netherlands

The TSO of the Netherlands (*Gasunie*) is a stakeholder of the Met4H2 project. This TSO considers that traceability of hydrogen is a key area to develop. A subsidiary company of Gasunie (*Hynetwork Services*) was appointed by the government to realise a Dutch hydrogen gas network. The objective is to have it completed by 2030. It will connect the major industrial hubs/ports in the Netherlands. This will primarily be done using existing but also newly constructed infrastructure [6] [7].

2.4.3 HyDelta project(s)

HyDelta (https://hydelta.nl/) is a public-private partnership, a Dutch national research programme and collaboration facilitating the large-scale implementation of hydrogen. Research results are published and freely available. The aim of the programme is to empower the hydrogen economy by resolving technical, scientific, and social barriers.

One of the resulting papers focuses specifically on flow metering [8]. The main conclusions are:

- USM (Ultrasonic meters) and thermal mass are the most likely candidates for domestic gas metering.

- Changes from laminar to turbulent flow may occur in hydrogen gas metering, their impact on performance remains unknown.
- Impurities may have significant effects on thermal mass meters.
- Control installations (calibration facilities operated by DSO) need adaptation to be able to inspect hydrogen meters.
- The traceability chain is mostly non-existent.

2.5 Norway

There is a very small domestic gas distribution network in Norway and no plan to deploy such infrastructure in the nearby future; the domestic gas distribution grid is in a limited area in the coastal south-western part of the country with about 2500 customers [9]. The Norwegian gas grid is connecting gas fields and the three gas processing plants in Norway or gas terminals abroad (Germany, Belgium, France, United Kingdom) [10]. Thus, this study is focusing on current and future uses of this grid to transport hydrogen.

The Norwegian gas grid is operated by Gassco (state-owned) and owned by Gassled (joint venture) [10]. Figure 5 shows the current pipeline network on the Norwegian shelf.

There is a common ambition between Norway and Germany to develop infrastructures by 2030, notably a pipeline able to transport hydrogen and CO_2 [11]. So far hydrogen is produced in Norway by Yara (producing ammonia) and Equinor (producing methanol), as grey hydrogen, used directly on site. The current infrastructure allows to transport H_2 and could be used to transport blue H_2 to Germany, but not CO_2 back [12]. Due to high pressures in subsea pipelines, hydrogen embrittlement is more likely, and a lower pressure may be forced to limit this issue, impairing the transport capacity to about 30% of the one of natural gas [13]. Novel compressor technology specifically designed for hydrogen may be necessary to limit pressure drop along the pipe [13]. Also, ammonia tankers are an economically viable option for the transport of H_2 and may compete against pipelines [12] [13].

The objective of the H_2 connexion between Norway and Germany is paired with several other hydrogen-related objectives such as commissioning of electrolysers and development of infrastructures for ammonia distribution [14]. Technical feasibility is validated by Gassco and the *German Energy Agency* (DENA), with a need of qualified equipment such as flow meters, regulations, standards and guidelines (Figure 6) [15] [16]. Both options of using the current pipeline *Europipe 1* or relying entirely on a new network are considered in the final report from Gassco and DENA; the order of magnitude of the flow is in millions of tonnes per year [16]. The relevance of using the *Europipe 1* will depend on the needs of Germany on natural gas, as its use for hydrogen will reduce the natural gas distribution capacity from Norway to Germany by 20-25 %; however, a new terminal for hydrogen in Germany will be anyway necessary [16]. A target of 10 GW of blue hydrogen from Norway to Germany is set by Equinor and other stakeholders [17].

Research is ongoing to ensure the technical resistance and sustainability of pipelines [18]. Development of pipelines seems to be the best option compared to cables, with a ratio of 13 to 1 when comparing the potential of energy transport [19].

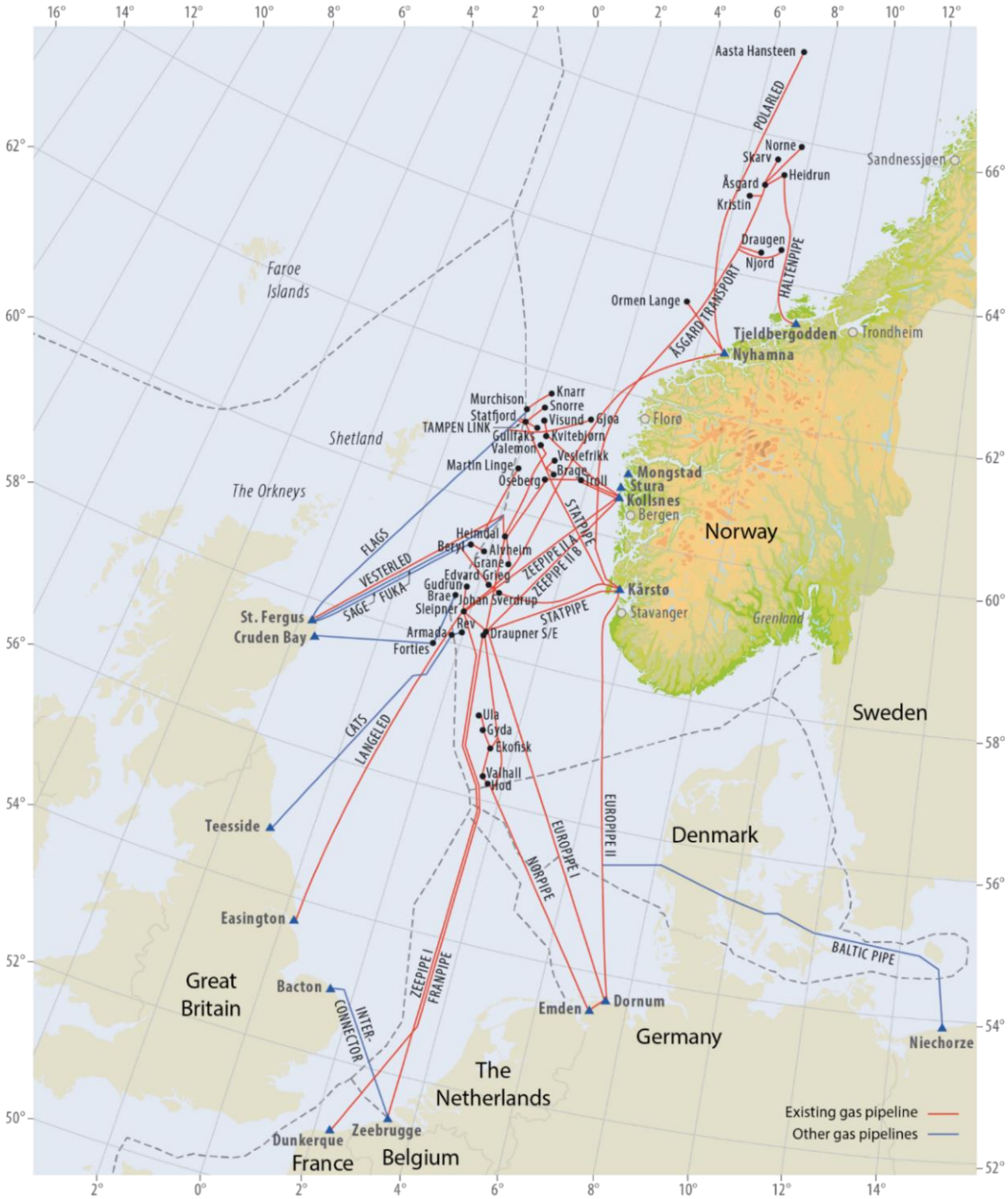

Figure 5: Map of gas grid in Norway. Taken from the websites of Norwegian Petroleum [10]. Interactive map available at Gassco's website. https://map.gassco.eu/map

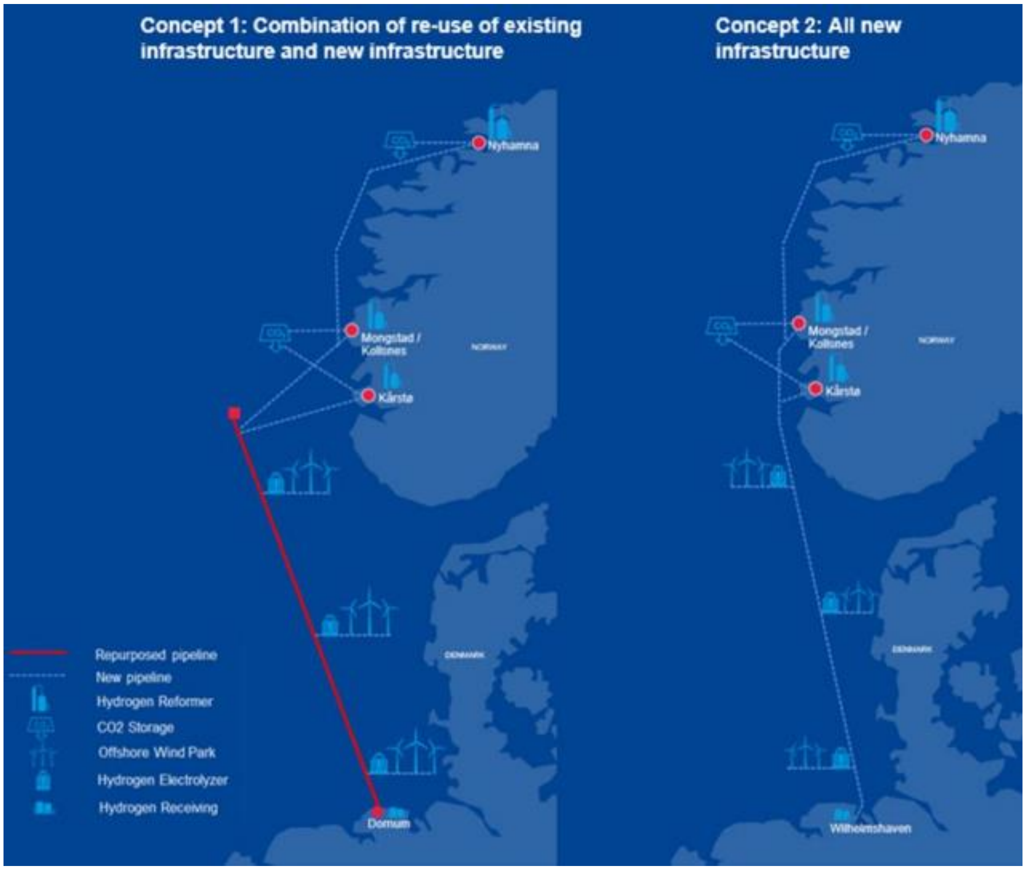

Figure 6: Offshore hydrogen transport concepts studied [16]

2.6 Denmark

A cooperation agreement was signed in March 2023 to establish hydrogen interconnectors to transport hydrogen made in Denmark (Figure 7) to German consumers. The plan covers deployment of 1,300 km of hydrogen pipelines up to 2045, as well as two dedicated hydrogen islands in the North Sea. The geological conditions in the North German lowlands are unique in Europe and ideally suited for the large-volume intermediate storage of hydrogen in caverns [20].

The first step toward establishing and operating the hydrogen infrastructure HySymbiosisNet has been taken. In 2023, a 0.5 km hydrogen pipeline was tested. One of the subsequent steps is to construct a 100 km long pipeline in 2026 [21]. The ClusterNortH2 project collaborates with Evida, Gas Storage Denmark, Eurowind Energy, and GreenLab. The completed pipeline is expected to be 170 km long, with a diameter of 12 inches and a pressure rating of 35 bar, facilitating the transportation of hydrogen throughout Northern Jutland (Figure 8) [22].

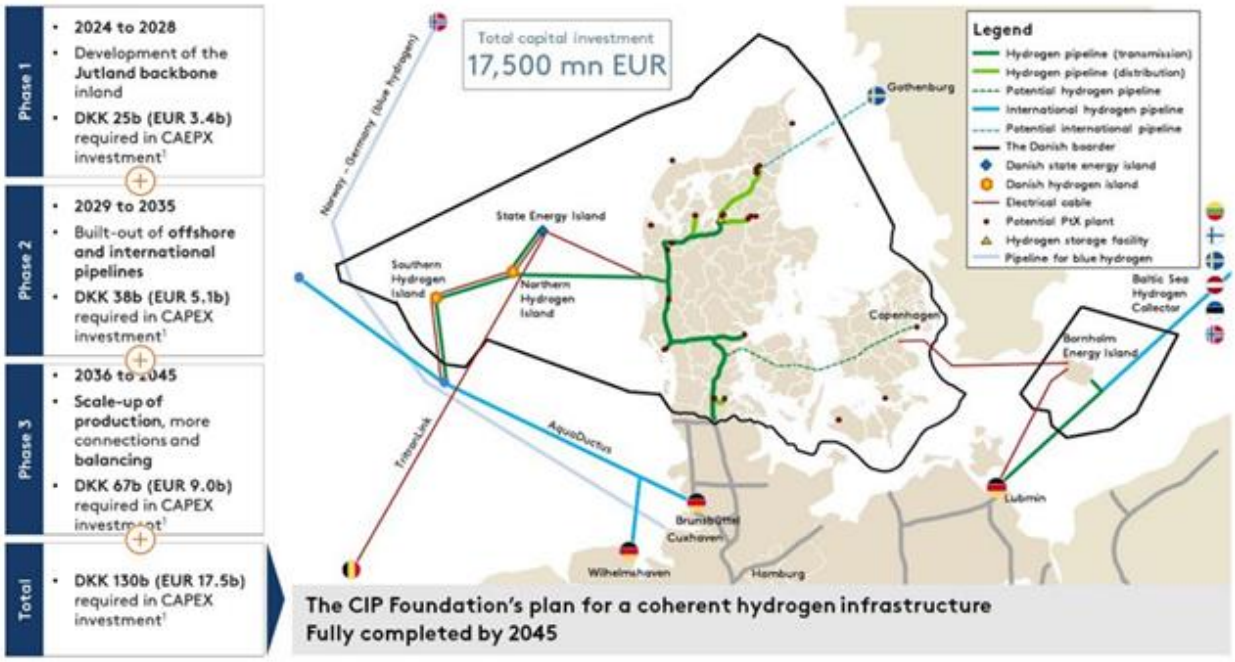

Figure 7: Hydrogen interconnection plans for transporting Danish hydrogen to German consumers.

Figure 8: The First plant hydrogen infrastructure in Denmark [22]

Energinet has announced plans to construct the West Jutland backbone, which will consist of a total pipeline length of approximately 360 km. The construction is scheduled to take place between 2025 and 2030, with a compressor station expected to be operational by 2038. To ensure future-proofing for the anticipated hydrogen market, an analysis indicates that the new pipes should be 36-inch in diameter, with a design pressure of 80 bar. Additionally, the existing natural gas pipeline in South Jutland, which currently has a diameter of 30 inches, could potentially be converted to accommodate hydrogen. The analyses suggest that there is no immediate capacity limitation (Figure 9) [23].

Figure 9: Hydrogen infrastructure in Denmark in 2030 [23]

There is also a website [24] that summarises plans for building hydrogen infrastructure in Denmark. Key topics on this web site include hydrogen quality and grid connection, system operation and balancing, and tariff design.

2.7 Czech Republic

There is so far no infrastructure in the Czech Republic where hydrogen is measured. The first commercial green hydrogen electrolyser in the Czech Republic was launched in 2023, with plans to launch more electrolysers in the coming years. This hydrogen will be consumed in cars or buses, or injected into the natural gas distribution network. For this case, two sites are being set up.

The most recent ambition of company EG.D, a.s. (DSO) is the Hype project (Hydrogen Project by E.ON Czech) in Mydlovary, which aims to build a production facility for green hydrogen in the South Bohemia region. The project will also include the construction of a test polygon where the effects of hydrogen on gas distribution system elements and metering will be investigated [25].

The company GASNET, s.r.o. (DSO) is planning two pilot projects in Aš-Trojmezí and Pardubice. 20 units of G4 gas meters (pure hydrogen and hydrogen-enriched natural gas), as well as rotary gas meters and operational safety are to be examined and tested in the long term [26].

2.8 United Kingdom

Although there is currently not a well-developed large-scale hydrogen pipeline in the United Kingdom (UK), based on the latest UK Hydrogen Strategy [27] published in August 2021, UK has plans to develop 'regional' or 'national' networks of hydrogen with large-scale storage sites, ideally by mid

2030s. Figure 10 shows Hydrogen Economy Roadmap of the UK. The figure has been taken from the UK Hydrogen Strategy document.

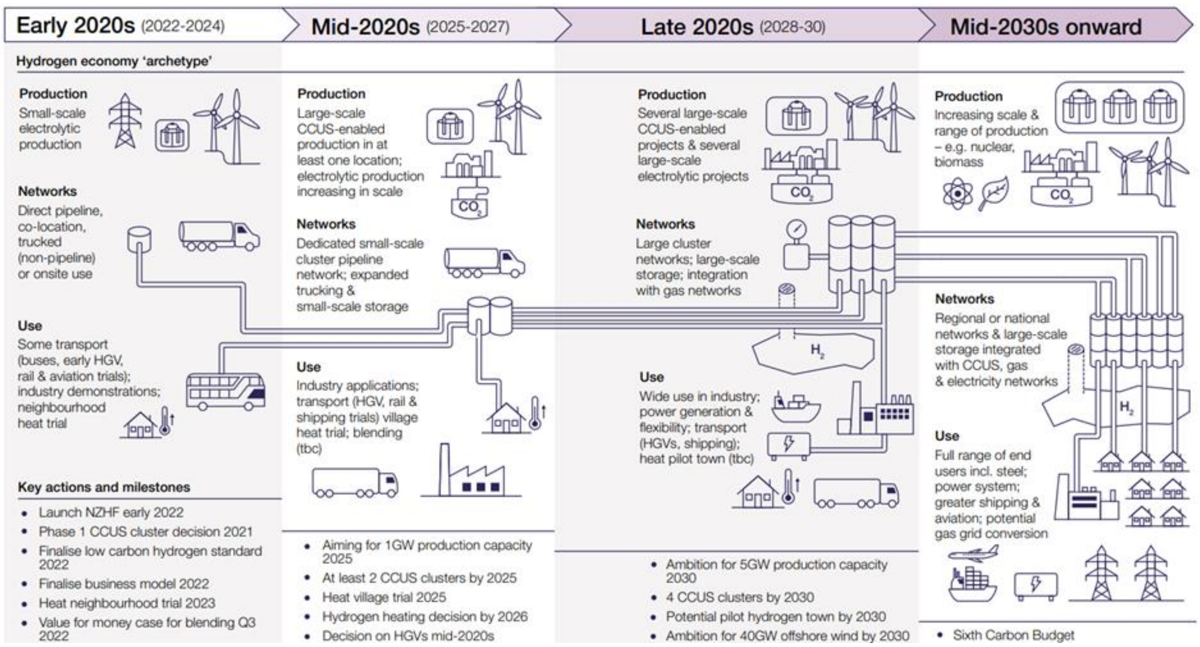

Figure 10: UK Hydrogen Roadmap (figure from UK Hydrogen Strategy, 2021 [27])

Making such a network will require the development of small and large-scale pipelines and flow measurement facilities that are suitable for hydrogen or hydrogen blends. UK is also investigating plans for the introduction of hydrogen into its existing natural gas network. Due to the complications that hydrogen can cause if it enters the gas network, the initial plan is to have a mixture of 20/80 percent of hydrogen/natural gas at the beginning and then to increase the percentage of hydrogen in increments, ideally up to 100%.

Another plan under investigation in the UK is to connect Scotland to the European Hydrogen Backbone (EHB) through a pipeline under the sea (Figure 11). This pipeline will be called Hydrogen Backbone Link (HBL) and will enable Scotland to export hydrogen to the European countries. The feasibility study of the development of HBL is now being undertaken by Net Zero Technology Centre (NZTC).

UK is also developing large scale test facilities for hydrogen. An example that is already developed and is currently operational is the Future Grid hydrogen test facility by National Gas.

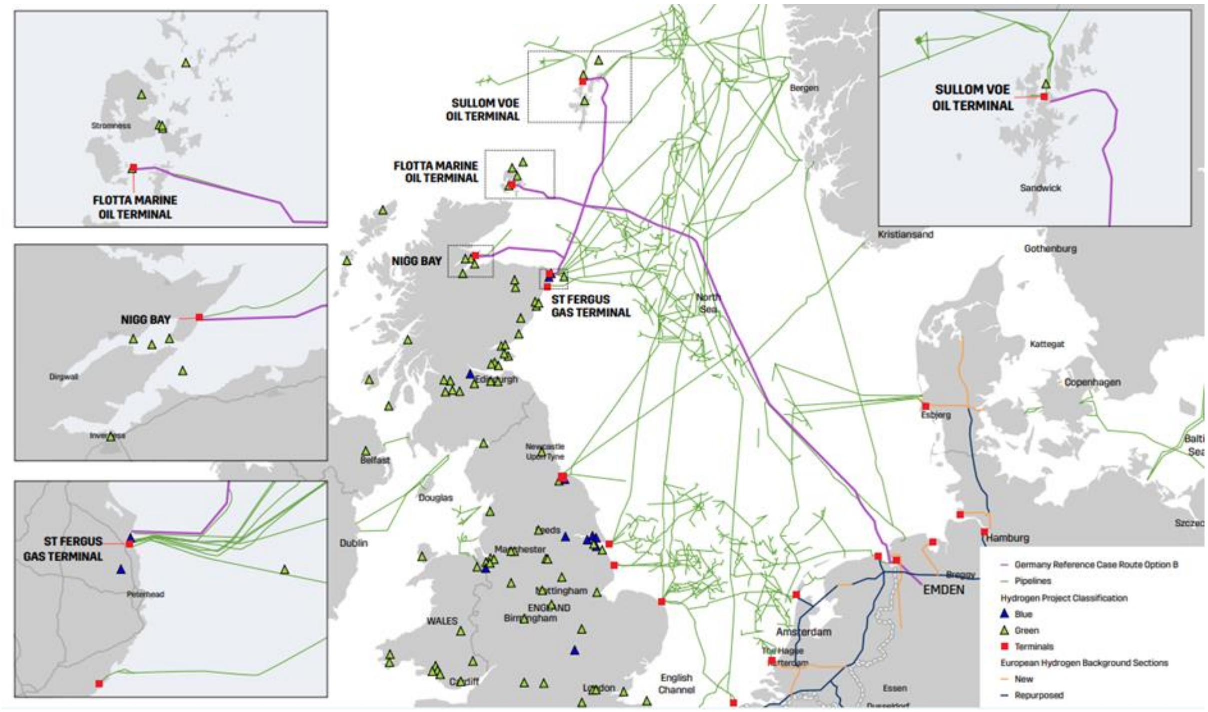

Figure 11: A possible route for the Hydrogen Backbone Link (Figure from the publicly available report of NZTC on Hydrogen backbone Link [28])

2.9 Italy

Figure 12 illustrates the existing hydrogen pipelines in Italy. They are located in Porto Marghera and Priolo Gargallo and owned by gas supplier companies (i.e., Air Products in and Air Liquide). These pipelines have limited lengths (1.63 km and 4.47 km, respectively) as they exclusively connect the hydrogen production sites to the end-users (i.e., chemical and petrochemical plants).

At present, the Decree of 3 June 2022 (Update to the Decree of the Minister of Economic Development of 18 May 2018, on: 'Technical regulation on the chemical and physical characteristics and presence of other components in fuel gas') sets the maximum blending concentration (i.e., the share of hydrogen in natural gas-hydrogen mixtures) to the 2% in volume. However, Snam Rete Gas (the national Transport System Operator-TSO) is committed to verify the compatibility of the existing network for the transport of natural gas-hydrogen mixtures with increasing percentages of hydrogen (up to 100%). Specifically, in April 2019, Snam Rete Gas began a verification process of its infrastructure by injecting a 5% hydrogen mixture into its natural gas transmission network in Contursi Terme (Salerno) with the aim of serving two local industries (a pasta factory and a mineral water bottling company) [29]. Furthermore, between 2019 and 2020, a second test was conducted in the same network segment exploring the injection of natural gas-hydrogen mixture with 10% of the hydrogen concentration [30]. In addition, in the framework of the National Recovery and Resilience Plan (PNRR), Snam is engaged in identifying the suitable locations to carry out the experiments required for updating the technical rules for the hydrogen transport in the gas network (Ministerial decree of 17 April 2008 and the Ministerial decree of 16 April 2008). SNAM is also evaluating the adoption of shared standard for hydrogen transport.

Figure 12: Hydrogen pipelines in Italy (modified from https://observatory.clean-hydrogen.europa.eu [1])

Figure 13: Italian hydrogen backbone [32]

Lastly, Snam is involved in the development of the Italian segment of the European Hydrogen Backbone (EHB). This pipeline will extend from the entry point in Sicily to the export points to Austria and Switzerland. This infrastructure could enable the transport of hydrogen produced in Northern Africa and Southern Italy to the main Italian and European consumption areas. As shown in Figure 13, the Italian Hydrogen Backbone will consist of around 2 300 km of pipelines (73% repurposed and 27% new built) and several compressor stations. With an import capacity of around 450 GWh/day from North Africa, this project is a major European corridor for renewable hydrogen import, serving Italian demand and with a capacity to export approximately 170 GWh/day to Austria and beyond [31].

2.10 Europe-wide distribution network

2.10.1 European Hydrogen Backbone

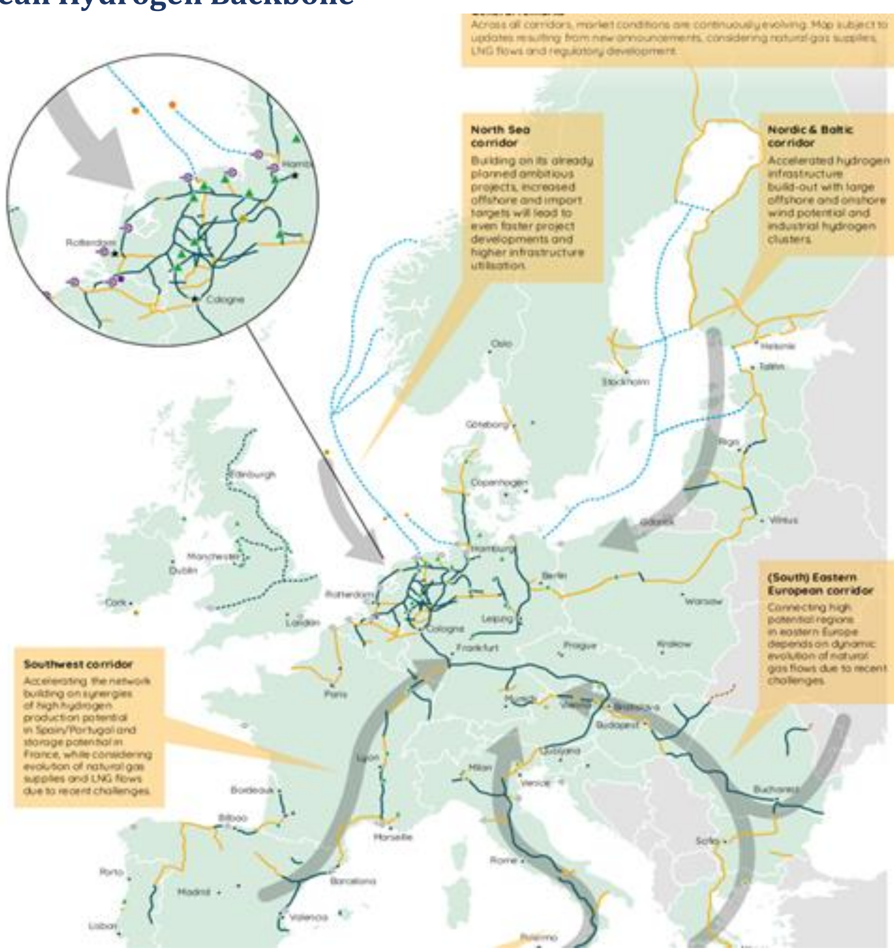

Figure 14: Plans of European Hydrogen Backbone

The initiative European Hydrogen Backbone (EHB) [33] was established in 2020. It is an initiative from a group of thirty-three energy infrastructure operators. The hydrogen infrastructure can then grow to become a pan-European network, with a length of almost 53 000 km by 2040, largely based on repurposed existing natural gas infrastructure (Figure 14).

Transporting hydrogen over 1 000 km along an average stretch of the onshore hydrogen backbone, as presented in this report, would cost €0.11 – €0.21 per kg of hydrogen transported (€3.3 - €6.3 per MWh). This cost estimate would be €0.17 - €0.32 per kg of hydrogen (€4.5 - €8.7 per MWh) per 1 000 km in case the hydrogen is transported entirely via dedicated subsea offshore pipelines. These figures confirm that the EHB is an attractive and cost-effective option for long-distance transport of hydrogen, considering an estimated future production cost of €1.0 - €2.0 per kg of hydrogen (€30 - €60 per MWh). These cost estimates represent a weighted average across a wide range of pipeline sizes and types – ranging from repurposed 20-inch pipelines to new 48-inch ones – assuming a pressure range of 20 to 78 bar (Figure 15) [34] – and also reflect their respective distance and capacity-weighted shares within the context of the overall European Hydrogen Backbone.

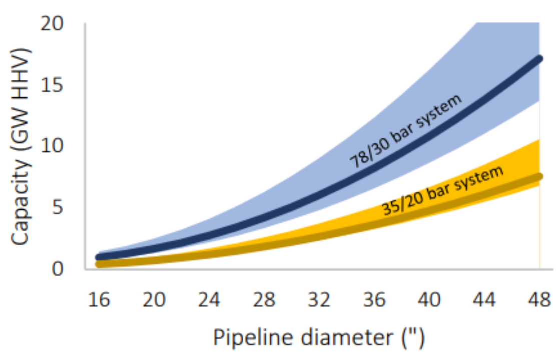

Figure 15: Transmission capacity in hydrogen pipes of various diameters. [34]

2.10.2 Central European Hydrogen Corridor

In September 2021, four leading Central European gas infrastructure companies joined forces to develop a hydrogen "highway" through Central Europe [35]. The focus of the joint initiative called the Central European Hydrogen Corridor (CEHC) is to transport hydrogen from promising future major hydrogen supply areas in Ukraine that offer excellent conditions for large-scale, green hydrogen production via Slovakia and the Czech Republic to large hydrogen demand areas in Germany and the EU. Its total length is around 1,225 km (Figure 16).

On 28th of November 2023, the European Commission adopted a decision to put Central European Hydrogen Corridor (CEHC) on its list of projects of common interest (PCI) and mutual interest (PMI) with a generic status.

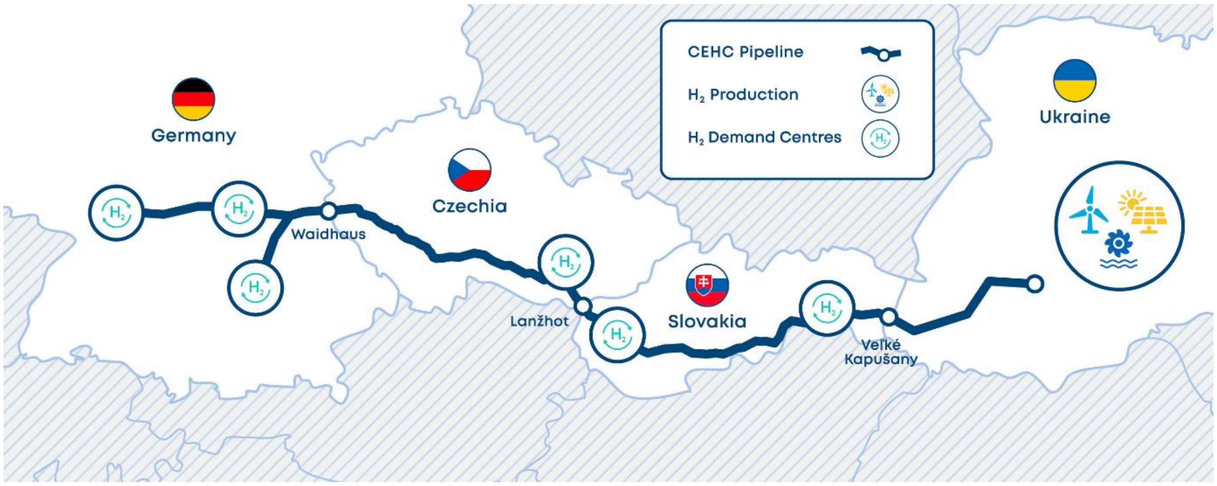

Figure 16: Central European Hydrogen Corridor

2.10.3 Project "Hydrogen in Gas Grids"

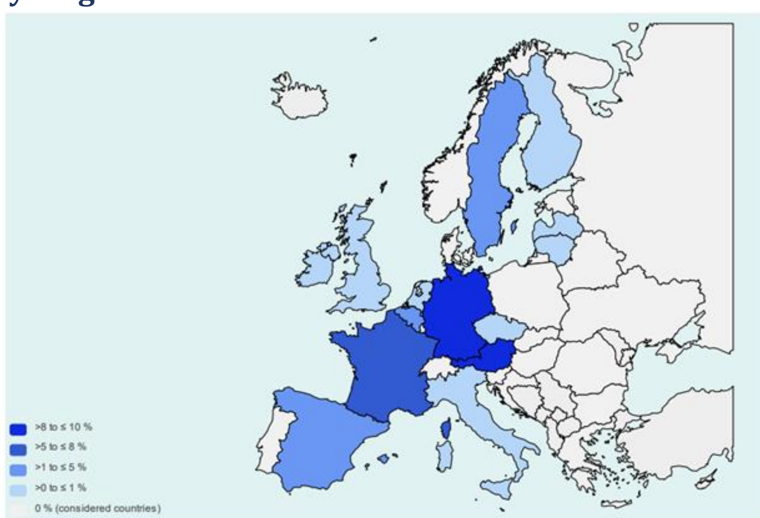

Figure 17: Allowed hydrogen concentration for blends with natural gas in the transit gas grids of the European countries [36]

The "Hydrogen in Gas Grids" (HIGGS) project [36] aims to pave the way to decarbonisation of the gas grid and its usage, this by covering the gaps of knowledge of the impact that high levels of hydrogen could have on the gas infrastructure, its components and its management. To reach this goal, several activities, including mapping of technical, legal and regulatory barriers and enablers, testing and validation of systems and innovation, techno-economic modelling and the preparation of a set of conclusions as a pathway towards enabling the injection of hydrogen in high-pressure gas grids, are developed in the project. During this project, a summary of hydrogen concentrations allowed in blends with natural gas in the transit gas grids of several European countries was created (Figure 17).

2.10.4 Project "H2med"

The H2med project has the ambition to interconnect Portugal, Spain, France and Germany with hydrogen pipelines. About 10% of the European hydrogen consumption could be transported using this corridor by 2030 (commissioning year). The pipelines CelZa (between Portugal and Spain) and BarMar (between Spain and France, offshore) are part of the network (dark green, Figure 18). The project relies on high renewable energy availability in Portugal and Spain [37].

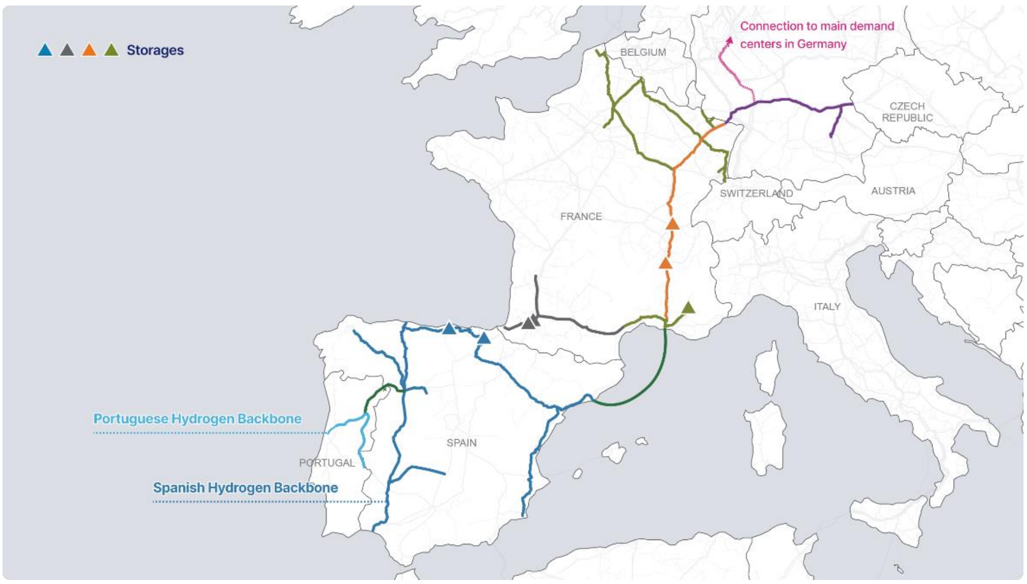

Figure 18: Routes of the pipelines within the H2Med project [37]

3 Suitability of using different gas flow meters for hydrogen measurement

3.1 Results of project 20IND10 DECARB (Metrology for decarbonising the gas grid)

In the report [38], techniques for hydrogen detection and determination of the percentage content of hydrogen in natural gas are mentioned. No results or recommendations are yet given in this project as to which instruments are suitable for measuring the flowing amount of hydrogen.

3.2 Results of project 18NRM06 NEWGASMET

The objective of the project 18NRM06 NEWGASMET [39] is to increase knowledge about the accuracy and durability of commercially available gas meters after exposure to renewable gases like biogas, biomethane, hydrogen, syngas and mixtures with natural gas.

During this project a static test with non-flowing hydrogen were performed with diaphragm gas meters, thermal mass gas meters and with domestic ultrasonic gas meters.

a. Summary of the results of diaphragm gas meters after durability tests with hydrogen

For the flow rates in the range of Q_t to Q_{max}, none of the differences in the errors after the durability test and the errors before the durability test exceed 2 %. All tested diaphragm gas meters were within tolerance of initial MPE for gas meters of accuracy class 1.5 before they were subjected to durability testing with hydrogen. The maximum difference was 0.52 %.

b. Summary of the results of thermal mass gas meters after durability tests with hydrogen

For the flow rates in the range of Q_t to Q_{max}, none of the differences in the errors after the durability test and the errors before the durability test exceed 2 %. A wider spread is observed with respect to diaphragm gas meter error shifts. All tested thermal mass gas meters were within tolerance of the initial MPE for gas meters of accuracy class 1.5 before they were subjected to durability testing with hydrogen. All tested thermal mass gas meters were within tolerance of twice the initial MPE for gas meters of accuracy class 1.5 after they were subjected to durability testing with hydrogen. The maximum difference was 1.15 %.

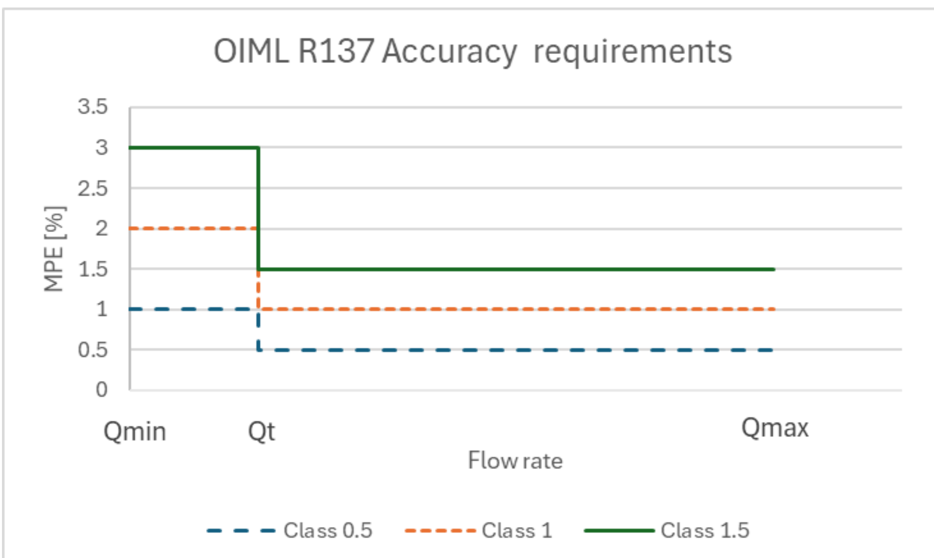

Figure 19: A summary of Maximum Permissible Error (MPE) as a function of flow rate (volumetric or mass), visualizing the different accuracy classes and the terms Q_{min}, Q_t and Q_{max}.

NEL and PTB developed calibration facilities with the required metrological quality according to OIML R137, this to carry out the accuracy tests required for conformity assessment of domestic gas meters with hydrogen or mixtures containing hydrogen. The uncertainty requirements for such tests given in OIML R137 (Figure 19) are fulfilled by the calibration facilities of both partners. From the calibrations using nitrogen and hydrogen, agreement between the results of PTB and NEL is acceptable for meters of Manufacturer B, even if there is no additional uncertainty influence by the meter shift considered. For all meters from both manufacturers there is no systematic difference when nitrogen and hydrogen is used as test gas. This statement is valid for diaphragm gas meter only, which can be understood from the fact that such a meter is based on a volumetric principle. Gas flow meters based on other operating principles must be investigated separately. Meters from Manufacturer A showed some differences between the results determined by the partners involved. These differences may be the result of damage to the meters during transport between the labs. Hence it is recommended to use meters selected for performance and do a very carefully packaging for such comparisons. In addition, shock sensors should be used to log mechanical stresses like severe shocks and vibrations.

When PTB calibrated the diaphragm meters with a wider range of test gases including methane and mixtures of hydrogen with methane, the permissible measurement deviations of ±3 % for $Q_{min} \leq Q < Q_t$ and ±1.5 % for $Q_t \leq Q < Q_{max}$ as required by EN 1359 were largely complied with. Whilst results differed for each test gas, there was no consistent trend towards positive or negative errors for any of the test gases. In summary, there was no overall tendency towards larger errors as hydrogen content in the test gases was increased.

For the thermal-mass domestic meter calibrated by NEL, there was a significant difference in the error curves for nitrogen and hydrogen. However, the metrological requirements of EN 17526:2021 for permissible errors, metrological stability, and gas-air relationship were achieved.

Using VSL's high-pressure Gas Oil Piston Prover primary standard (GOPP), the effect of mixing hydrogen with natural gas on the accuracy of a high-pressure flow meter was assessed for the first time. The accuracy of a G100 rotary flow meter was determined by direct calibration against primary reference values. The rotary flow meter was calibrated using both NG and HENG, at two different pressures: 9 bar and 16 bar. Although differences between errors with NG and HENG are mostly negative, these changes are insignificant from a metrological standpoint. Results indicate that, for the rotary flow meter and hydrogen admixtures ($<20 \times 10^{-2}$ mol/mol H_2) used, the meter error differences between high-pressure hydrogen admixture calibration and high-pressure natural gas calibration are smaller than the meter error differences between atmospheric pressure air calibration and high-pressure natural gas calibration.

3.3 DVGW project G202010 - Investigation of the behaviour of domestic gas meters in combination with house pressure regulators when using H_2 enriched gases

This project took place in the period 10.2020 - 08.2022 [40]. DVGW (Deutscher Verein des Gas- und Wasserfaches) together with PTB tested diaphragm gas meters. The tests were carried out with the fuel gases methane, methane with up to 30 % admixture of hydrogen as well as for pure hydrogen, as the Wobbe index for these gases is still within or slightly outside the limits of DVGW requirement. As no systematic gas type influence on the measurement and control behaviour were observed, the range above 30 % admixture of H_2 can also be regarded as metrologically safe. The analysed outlet pressure of the domestic pressure regulators shows that the gas type has no significant influence on the control quality. The results of the tests were within the limits specified by the relevant normative documents, which must be legally complied with in Germany, typically by the Measurement and Calibration Ordinance. Only minor differences were found between the error curves of the diaphragm gas meters when pressurised with the various gases or gas mixtures during the metrological investigation. The household pressure regulators have no influence on the measurement deviation of the diaphragm gas meters. The calibration and adjustment for conformity assessment of pressure regulators and diaphragm gas meters, which are intended for measuring H_2 natural gas mixtures or pure hydrogen, can be carried out using air as the test gas. This means that there are no additional production costs. The gas meters analysed in this project were as good as new devices whose error curves were accordingly within the calibration error limits and which show the lowest possible absolute error values in the entire flow range as a result of the adjustment.

3.4 Domestic Gas Meter Durability in Hydrogen and Natural Gas Mixtures

The *Oil and Gas Institute - National Research Institute* in Poland and *Department of Civil and Mechanical Engineering, University of Cassino and South Lazio* in Italy tested diaphragm and thermal mass gas meters for durability with hydrogen-enriched natural gas [41]. The tests were carried out for 2E natural gas and natural gas mixtures with hydrogen additions of 5 %, 10 % and 15 % (v/v) for 5000 and 10 000 h. Some of the diaphragm gas meters were tested for even 15 000 h, and the tests of the thermal gas meters were completed after 7 500 h. The general conclusions resulting from the obtained results are as follows:

- For the test samples subjected to the durability tests, regardless of whether they were gas meters in service (after 10 years of operation) or new gas meters, no significant metrological influence of added hydrogen was found on the obtained average drift of errors of indications after the durability tests. Apart from a single Type−1 gas meter tested in sample 2E/H0 (without hydrogen addition), in which most likely internal leakage occurred, the gas meters meet the metrological requirements for a durability test according to EN 1359.
- For most diaphragm gas meters and for thermal gas meters, no statistically significant influence of the hydrogen content in the gas was found on the change in gas meter errors of indications after they were subjected to the durability tests. For the new Type−4 diaphragm gas meters and in-service Type−7 gas meters, after the 10 000 h durability test, statistically significant differences were found in the average drift of the errors of indications of gas meters subjected to the durability test with a 2E natural gas mixture with 15 % hydrogen addition and 2E natural gas without hydrogen at flow rates $0.4Q_{max}$, $0.7Q_{max}$, $3Q_{min}$ and Q_{max}, respectively. Analysing the average drift of errors of indications for the control sample 2E/H0 and the test sample 2E/H15, it can be concluded that the differences between these changes are smaller than the uncertainty of determining the difference, and therefore these should be considered metrologically insignificant.
- For all types of gas meters subjected to the durability test after 10 000 h, no significant differences were found between the average weighted mean error (WME) changes for the tested gas mixtures, and almost all gas meter errors were within ±1.2 %, except for single gas meters (4 meters from 105 pieces).
- During the durability tests, no damage was found that would compromise operational safety. All gas meters - diaphragm or thermal - remained tight after the durability tests.

- The tests carried out with the use of diaphragm gas meters, both new and after 10 years of operation, as well as thermal gas meters, indicate that they can be used for the settlement purposes of natural gas with the addition of hydrogen at a concentration up to 15 %. Nevertheless, it should be noted that research in the field of flow metrology should still be carried out because the discussed results concern only a certain group of gas meters, which is not representative of all types of gas meters used.

3.5 Declarations from manufactures of gas meters

Companies Apator Metrix S.A., ELEKTROMETAL S.A., Elster GmbH, Dresser Utility Solutions GmbH, MeteRSit have stated that a large number of their gas meters (diaphragm, thermal mass, rotary piston gas meters) are capable of measuring natural gas with hydrogen content or pure hydrogen. For higher flow rates and higher pressures, ultrasonic gas meters can be used. Several manufacturers such as RMG Messtechnik GmbH, KROHNE Messtechnik GmbH, SICK AG and others declare that their ultrasonic gas meters are capable of measuring the flowing amount of hydrogen or hydrogen-enriched natural gas.

4 Normative documents

Considering the complexity of the technologies as well as the time needed to develop standards representing the 'State of the Art' (typically requiring a few years), a development plan with priorities for such standards should be established and be initiated as soon as possible. It is essential that standards are developed in a timely fashion ensuring alignment with the legal/regulatory framework and development of technologies. That is why *European Clean Hydrogen Alliance (ECH2A)* [42] and *CEN* issued ROADMAP ON HYDROGEN STANDARDISATION [43].

Physikalisch Technische Bundesanstalt (Germany) issued *Technical Guidelines for Measuring instruments for Gas* **G 19** [44] which states that:

In principle, there are no objections to the use of gas meters of any technology approved for natural gas for the measurement of hydrogen-enriched natural gases with substance quantity fractions $x_{H2} \leq 5$ %. Use of these meters up to $x_{H2} = 10$ % is permitted if the manufacturer explicitly authorises this in the relevant documentation (e.g. operating manual). Use above $x_{H2} = 10$ % is only permitted with a corresponding manufacturer's declaration and a clearance certificate from the PTB.

5 Conclusion

This literature study has covered the use of hydrogen in gas pipelines in Europe, including both the gas distribution network and any specific plans to use the network to transport hydrogen. The study highlights that a lot of countries in Europe are taking part in developing a well-connected hydrogen pipeline network. The network could potentially start from Norway and Finland, extends through the sea to Germany, and continues all the way to Italy, with the possibility of further extension to Greece. Secondly, the North Sea is expected to have a great influence on green energy production, particularly in the context of green hydrogen. This influence extends to countries such as Denmark, Norway, the Netherlands, Belgium, Germany, Great Britain, and France. Thirdly, in Central Europe, hydrogen production is anticipated in Ukraine. A CEHC pipeline will transport hydrogen to Czechia, Slovakia, and Germany. Overall, this network could span 53,000 kilometres with expected pipes from 20 to 48-inch in diameter, with a design pressure of 80 bar, and serve as a backbone for European hydrogen infrastructure. It has made use of material provided by participants in the project *21GRD05 Metrology for the hydrogen supply chain* (Met4H2) project.

In general, this is a new and emerging industry and energy sector, and so the data collected on actual use and long-term experience for each type of meter used for hydrogen measurement is not extensive. From the data obtained, it can be expected that diaphragm gas meters would be used to measure hydrogen and its mixture with natural gas for smaller flow rates, up to approximately 16 m^3/h, and that they have performed slightly better than thermal mass gas meters. For higher flow rates, up to approximately 400 m^3/h, rotary gas meters will probably be used, and ultrasonic gas meters for even higher flow rates. For higher pressures, Coriolis flow meters could be an option, although there is little research so far done on these flow meters.

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