Technical Report on the current status and future plans within the European gas distribution grid, models for hydrogen flow, and liquid hydrogen supply chains

Technical Report

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Authors Tomáš Valenta CMI		Corresponding author Tomáš Valenta
Contributing partners Bernhard Rotter BEV-PTP, Rémy Maury CESAME, Hamidou Soumaré CESAME, Lucie Dangeon-Vassal CESAME, Kurt Rasmussen FORCE Technology, Loucie Cirkeline Nordhjort Mjølna FORCE Technology, Edvardas Venslovas JV, Maxime Mussard JV, Marcel Workamp VSL, Menne Schakel VSL, Mahdi Sadri NEL, Eric Starke SICK, Massimo Santarelli POLITO, Marc de Huu METAS		
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1 Introduction

Hydrogen will play a key part in the energy mix in the near future, and its transportation and measurement present growing challenges. Understanding and solving these challenges can strongly influence the development of hydrogen technology.

This technical report is a part of the *European Partnership on Metrology* Project 21GRD05 Met4H2 *Metrology for the hydrogen supply chain*. The objective of this document is to provide input to stakeholders on the issues related to transport and measuring of hydrogen. An overview of the current status and future plans for measurement of hydrogen and transport within Europe is given; emphasis is put on the European gas distribution grid, the models for hydrogen flow, and the liquid hydrogen supply chains; also, the uncertainty of hydrogen flow meter calibrations for relevant supply chains, including relevant flow metering technologies, is discussed. A summary of these outputs can be found at the end of the document.

In the future, it can be assumed that hydrogen will be used and transported both in its gaseous state and as a liquid. Both of these states have their own specific advantages and disadvantages in their use and transport.

When using hydrogen gas, it is necessary to be careful about its high explosiveness. Hydrogen is the smallest molecule, which makes it a substance with high volatility and the ability to escape through even small leaks in pipes. Steels, especially high-strength ones, can absorb hydrogen, which may lead to hydrogen embrittlement.

When transporting liquid hydrogen, it is necessary to maintain a temperature of -253 °C maximum. Double walls with vacuum insulation and multi-layer barriers must be used to minimize heat transfer. Furthermore, it is necessary to solve the problem of evaporation (boil-off effect).

The sections below summarize real examples showing how both gaseous hydrogen and liquid hydrogen are currently or are planned to be transported.

2. Hydrogen gas distribution grids

2.1. European Hydrogen Backbone

The initiative European Hydrogen Backbone (EHB) [1] was established in 2020. It is an initiative from a group of thirty-three energy infrastructure operators. By 2040, hydrogen infrastructure could evolve into a trans-European network spanning nearly 53 000 kilometers, primarily utilizing converted natural gas pipelines (see Figure 1).

According to the data presented, transporting hydrogen over a distance of 1 000 kilometers via a typical segment of the onshore hydrogen backbone would cost between €0.11 and €0.21 per kilogram of hydrogen, equivalent to €3.3 to €6.3 per MWh. If the hydrogen were instead transported entirely through purpose-built offshore subsea pipelines, the cost would rise to €0.17–€0.32 per kilogram

(€4.5–€8.7 per MWh) for the same distance. These cost projections highlight that the European Hydrogen Backbone (EHB) represents a viable and economically efficient solution for long-range hydrogen transport, particularly when compared to a projected future production cost of €1.0–€2.0 per kilogram (€30–€60 per MWh) [1].

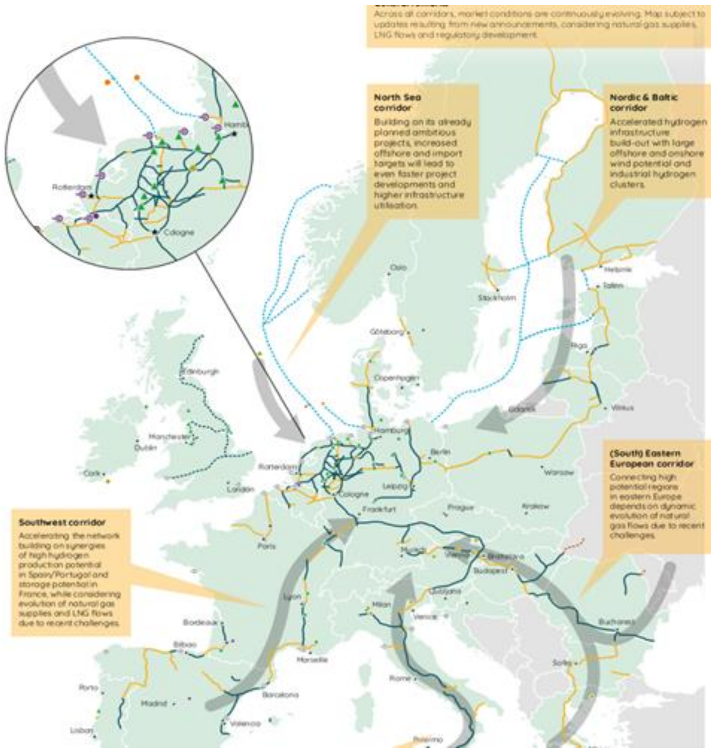

Figure 1: Plans of European Hydrogen Backbone

2.1.1. Central European Hydrogen Corridor

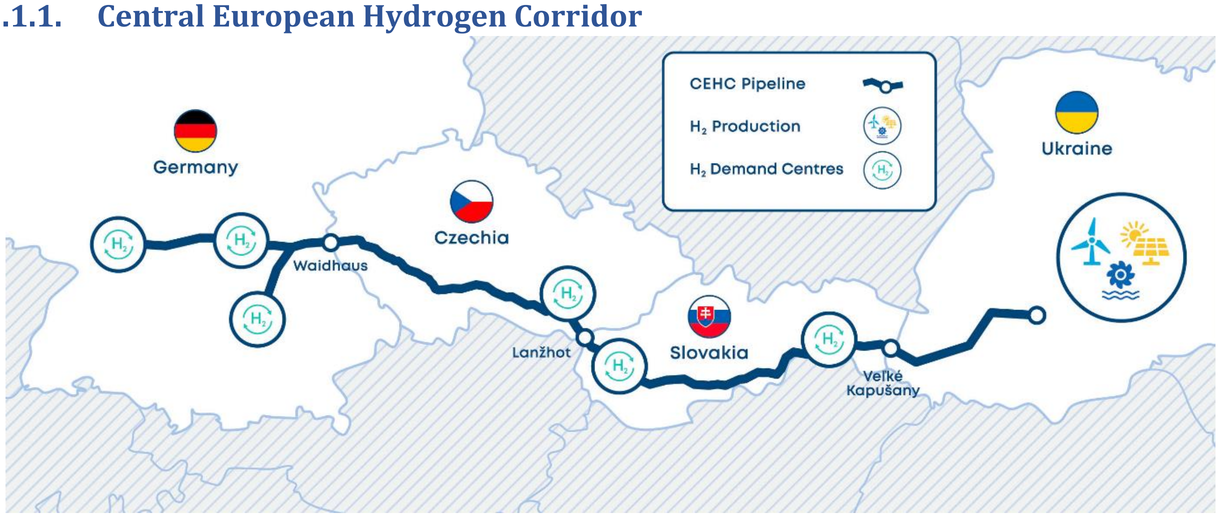

Figure 2: Central European Hydrogen Corridor

In September 2021, four major gas infrastructure operators from Central Europe formed a partnership aimed at establishing a hydrogen "highway" through the region [2]. This collaborative project, known as the Central European Hydrogen Corridor (CEHC), is designed to enable the transportation of hydrogen from Ukraine—an area with strong potential for large-scale green hydrogen production—through Slovakia and the Czech Republic, ultimately delivering it to key demand centers in Germany and across the European Union. Its total length is around 1 225 km (Figure 2).

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 [2].

2.1.2. Project "Hydrogen in Gas Grids"

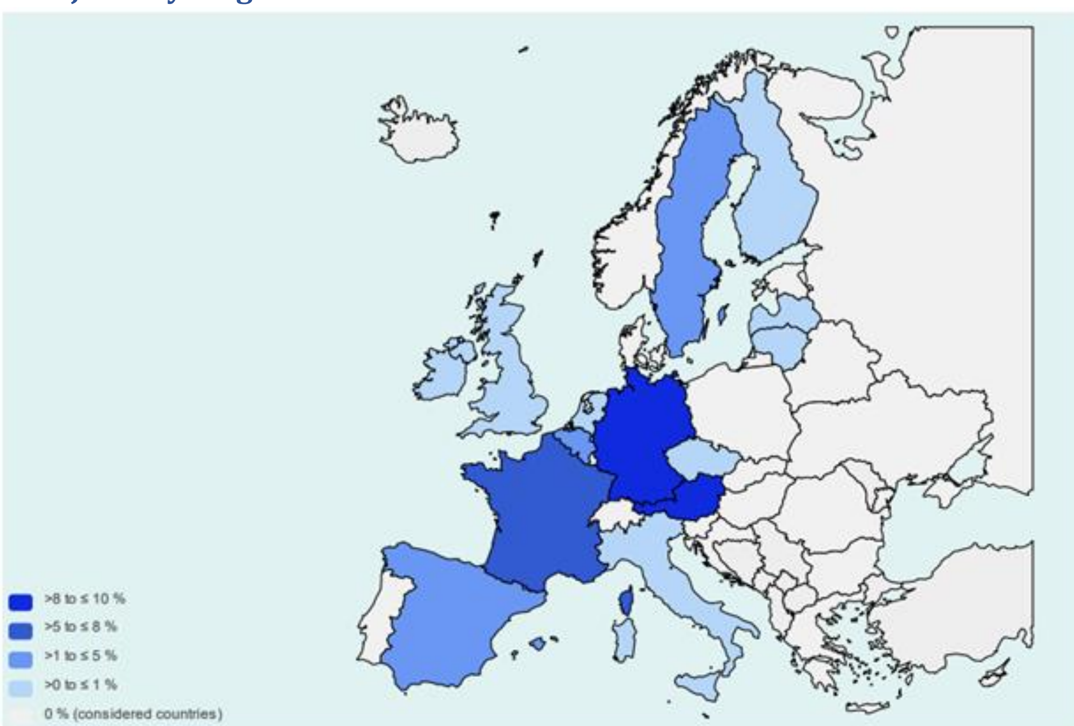

Figure 3: Allowed hydrogen concentration for blends with natural gas in the transit gas grids of the European countries [3]

The "Hydrogen in Gas Grids" (HIGGS) project [3] is dedicated to supporting the decarbonization of gas networks and their operation by addressing existing knowledge gaps regarding the effects of high hydrogen concentrations on gas infrastructure, its components, and overall system management. To achieve this objective, the project carries out a range of activities, such as identifying technical, legal, and regulatory challenges and opportunities, conducting testing and validation of systems and innovations, performing techno-economic modelling, and formulating a set of recommendations that serve as a roadmap for enabling hydrogen injection into high-pressure gas networks. [3]. 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 3) [3].

2.1.3. 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 4). The project relies on high renewable energy availability in Portugal and Spain [4].

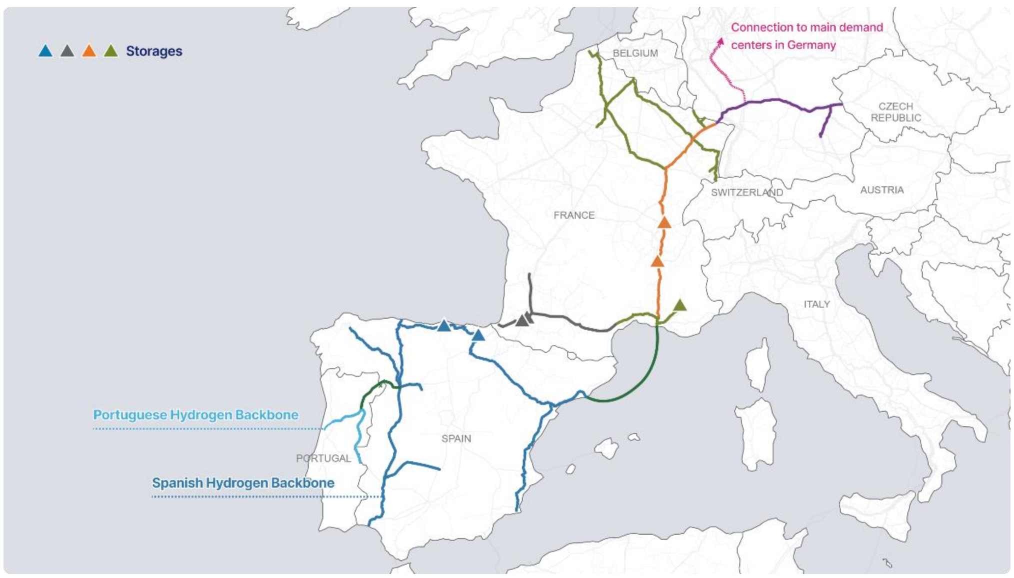

Figure 4: Routes of the pipelines within the H2Med project [4]

2.2. National gas hydrogen distribution grids

2.2.1. Belgium

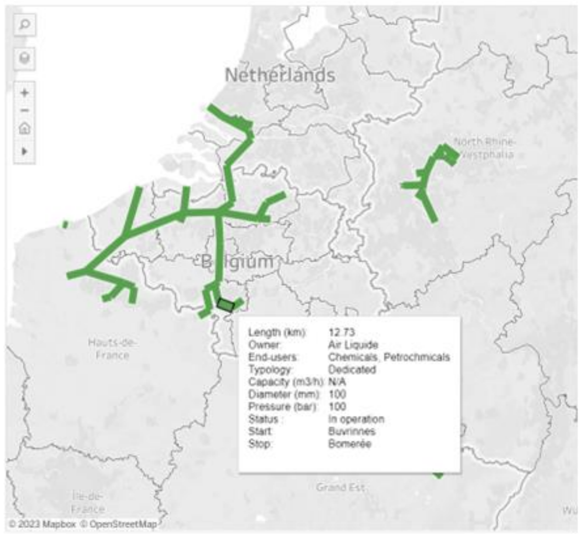

Figure 5: Hydrogen distribution networks located in Belgium

The website https://observatory.clean-hydrogen.europa.eu/ shows that the hydrogen distribution networks in Europe are mainly located in Belgium (Figure 5). The owner of these networks is the company Air Liquide [5]. In Belgium, the network is 964 km long and the end users are chemical and petrochemical companies.

2.2.2. Germany

The website https://observatory.clean-hydrogen.europa.eu/ shows that some others hydrogen distribution networks in Europe are located in Germany (Figure 6). The owners of these networks are companies Linde and Air Liquide [5]. In Germany, the network is 257 km long and the end users are chemical and petrochemical companies.

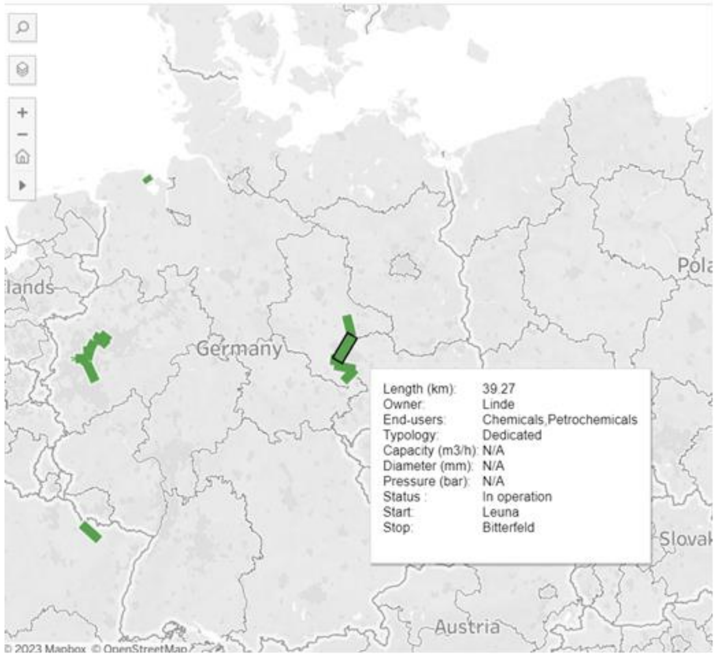

Figure 6: Hydrogen distribution networks located in Germany

The economic development agencies of Germany's northern states—Bremen, Hamburg, Mecklenburg-Vorpommern, Lower Saxony, and Schleswig-Holstein—have come together to launch HY-5, a joint initiative focused on promoting green hydrogen [6] (Figure 7). 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.

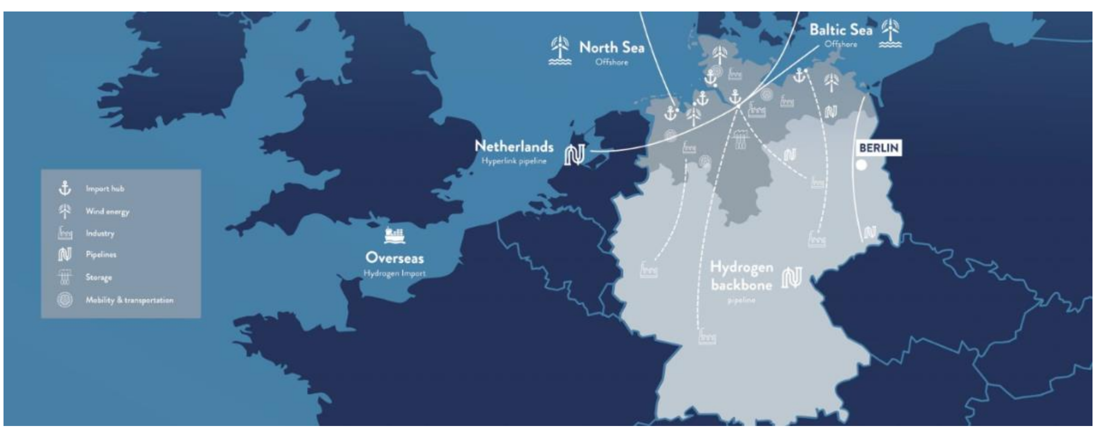

Figure 7: Initiative HY-5 in Germany

2.2.3. France

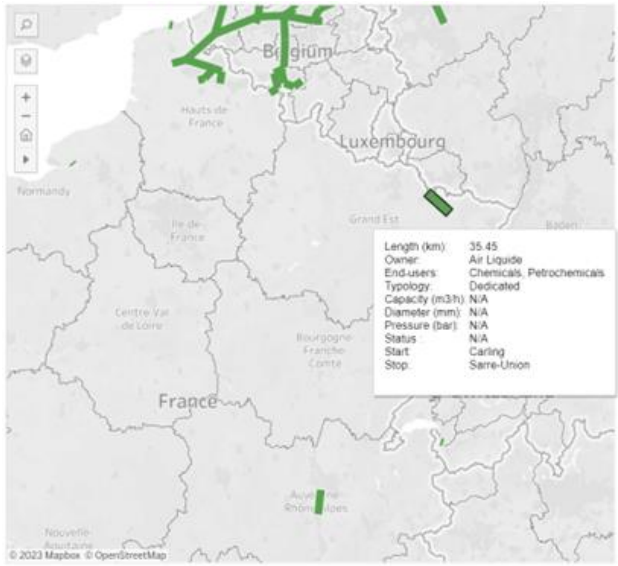

Figure 8: Hydrogen distribution networks located in France

The website https://observatory.clean-hydrogen.europa.eu/ shows other hydrogen distribution networks in Europe located in France (Figure 8). The owner of these networks is the company Air Liquide [5]. In France, the network is 215 km long and the end users are chemical and petrochemical companies.

2.2.4. The 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 [5].

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 [10].

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

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

In the city of Lochem [7], 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 towns Stad aan 't Haringvliet [8] and Rozenburg [9]. In Rozenburg, two hydrogen boilers were installed in an apartment complex.

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 [10] [11].

HyDelta project(s) in the Netherlands

HyDelta (https://hydelta.nl/) is a collaborative effort between public and private entities, functioning as a national research program in the Netherlands that supports the widescale deployment of hydrogen. The initiative makes its research findings publicly accessible. Its primary goal is to advance the hydrogen economy by addressing and overcoming scientific and technical challenges [12].

One of the resulting papers focuses specifically on flow metering [12]. The main conclusions are:

- USM (Ultrasonic meters) and thermal mass meters 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.

2.2.5. Norway

There is a very small domestic gas distribution network in Norway and no plans 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 [13]. 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) [14]. 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) [14]. Figure 9 shows the current pipeline network on the Norwegian shelf.

There was a common ambition between Norway and Germany to develop infrastructures by 2030, notably a pipeline able to transport hydrogen and CO_2 [15] but unfortunately this project was terminated. 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 [16]. 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 [17]. Novel compressor technology specifically designed for hydrogen may be necessary to limit pressure drop along the pipe [17]. Also, ammonia tankers are an economically viable option for the transport of H_2 and may compete against pipelines [16] [17].

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 [18]. 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 10) [19] [20]. 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 [20]. 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 % to 25 %; however, a new terminal for hydrogen in Germany will be anyway necessary [20]. Unfortunately, a target of 10 GW of blue hydrogen from Norway to Germany set by Equinor and other stakeholders was terminated [21].

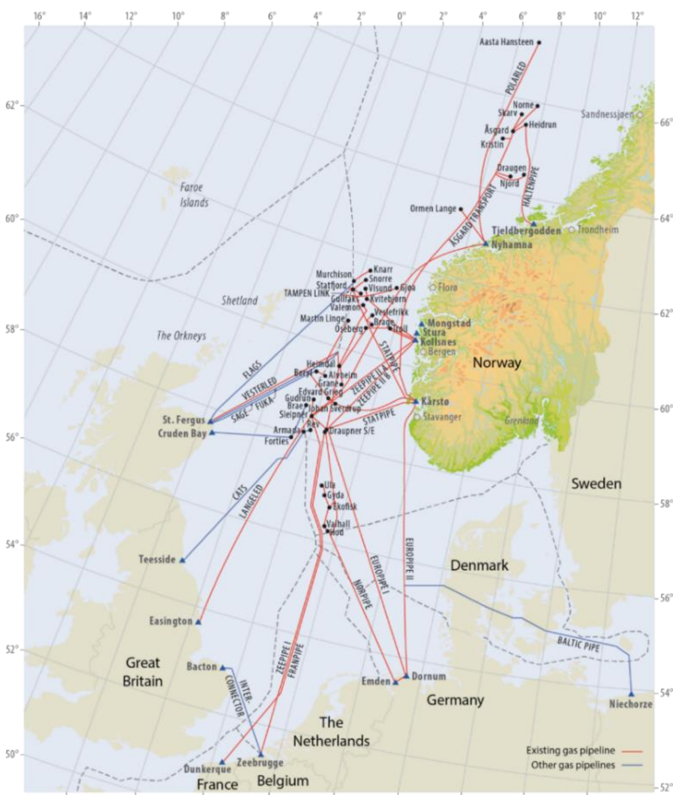

Figure 9: Map of gas grid in Norway. Taken from the websites of Norwegian Petroleum [14].

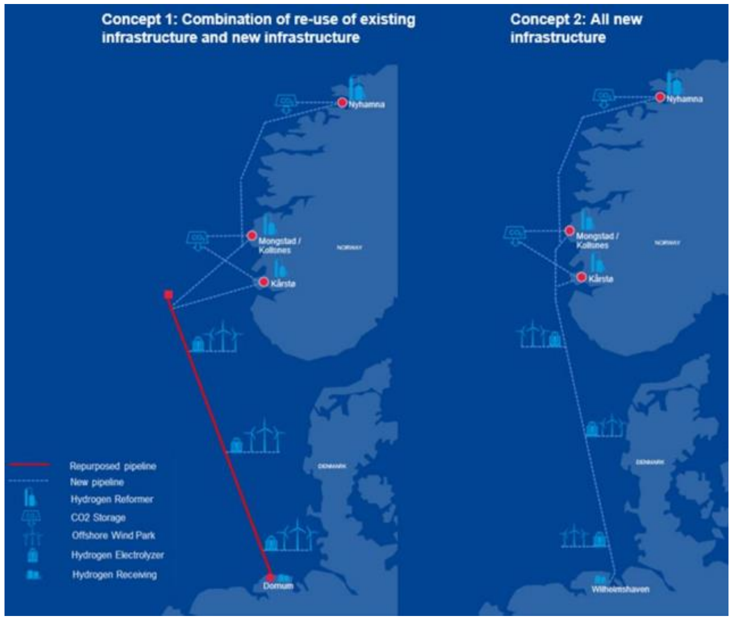

Figure 10: Offshore hydrogen transport concepts studied [20]
(Now terminated with the conclusion that it will not be realised.)

2.2.6. Denmark

A cooperation agreement was signed in March 2023 to establish hydrogen interconnectors to transport hydrogen made in Denmark (Figure 11) 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 [24].

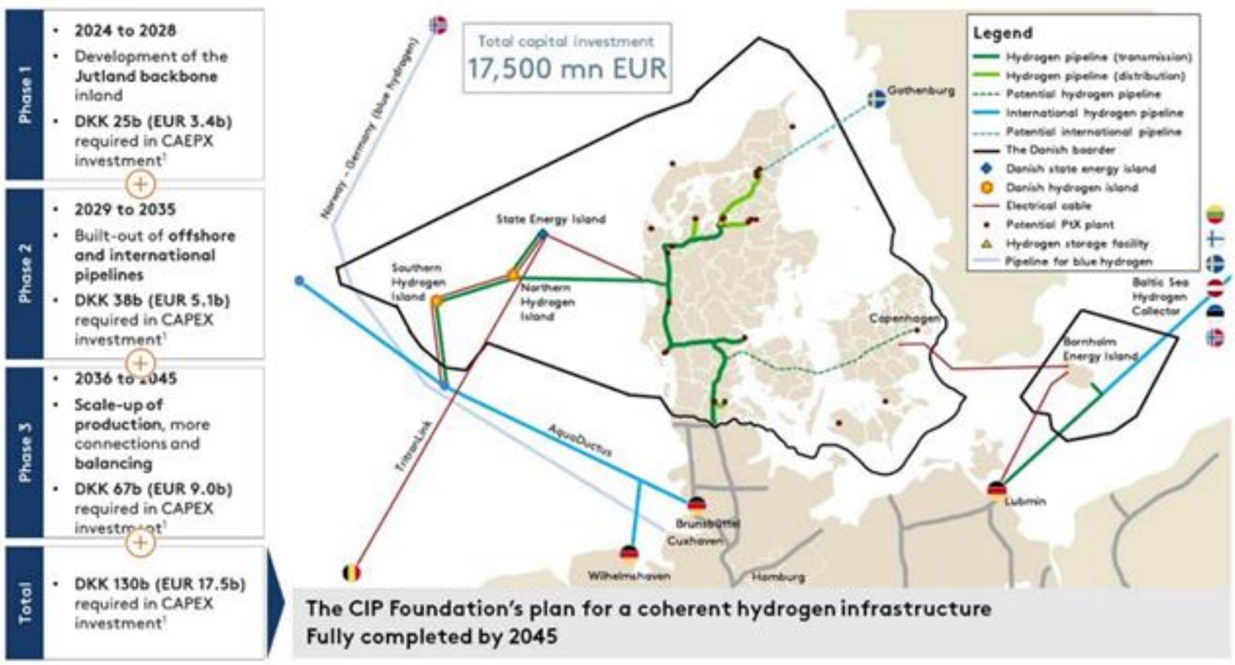

Figure 11: Hydrogen interconnection plans for transporting Danish hydrogen to German consumers [24].

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 2028 [25]. The ClusterNortH2 project collaborates with Evida, Gas Storage Denmark, Eurowind Energy, and GreenLab [26].

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 2028 and 2032, 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 analysis suggests that there is no immediate capacity limitation (Figure 12) [27].

Figure 12: Hydrogen infrastructure in Denmark in 2032 [23]

There is also a website [28] 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.

2.2.7. 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 by cars or buses, or injected into the natural gas distribution network. For this purpose, 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 [29].

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 [30].

2.2.8. United Kingdom

Although there is currently no well-developed large-scale hydrogen pipeline in the United Kingdom (UK), based on the latest UK Hydrogen Strategy [31] published in August 2021, there are plans to develop ‘regional’ or ‘national’ networks of hydrogen with large-scale storage sites, ideally by mid 2030s. Figure 13 shows the Hydrogen Economy Roadmap of the UK. The figure has been taken from the UK Hydrogen Strategy document.

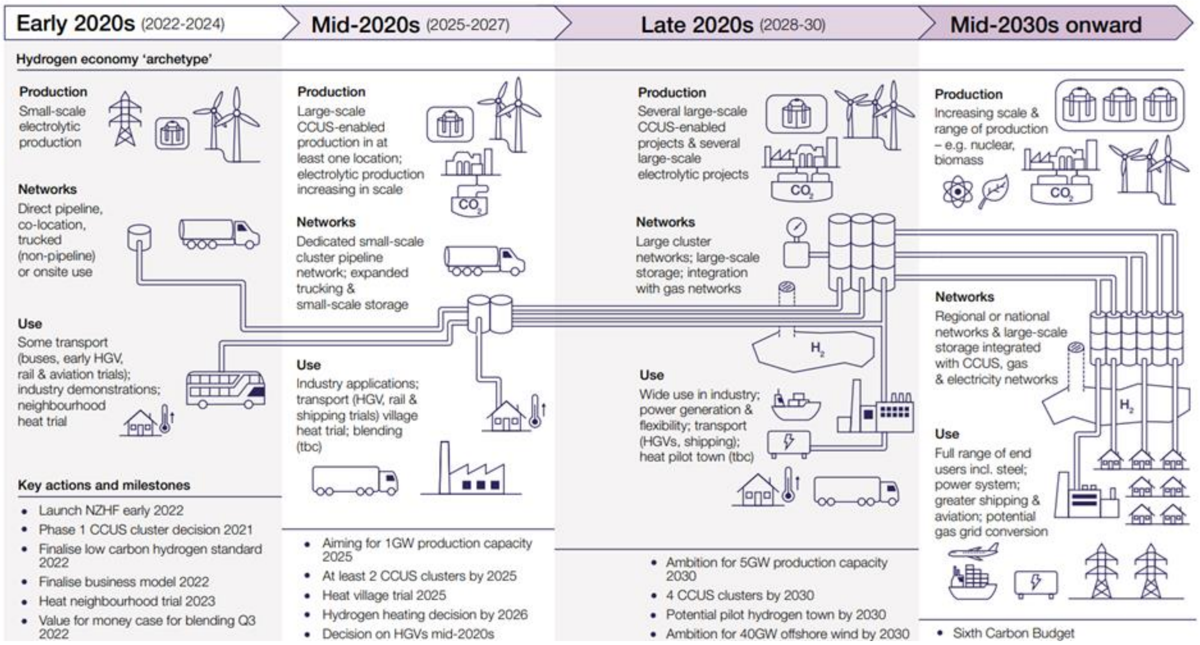

Figure 13: UK Hydrogen Roadmap (figure from UK Hydrogen Strategy, 2021 [31])

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 14). 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.

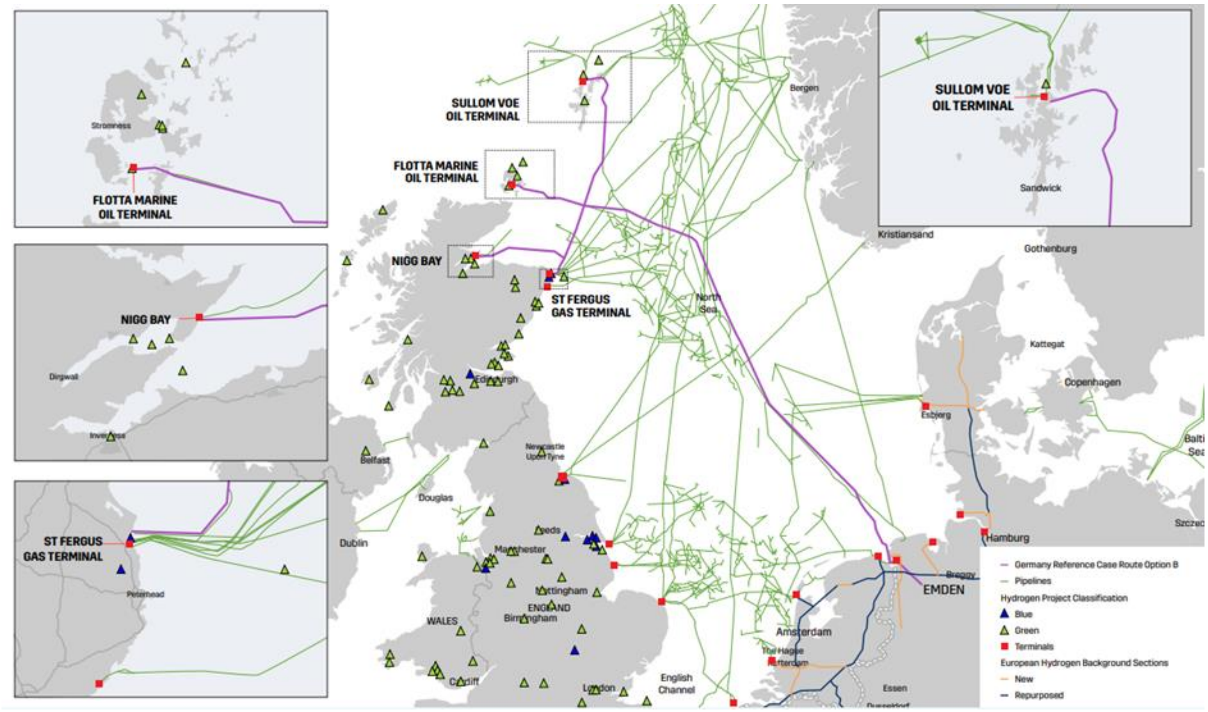

Figure 14: A possible route for the Hydrogen Backbone Link (Figure from the publicly available report of NZTC on Hydrogen backbone Link [32])

2.2.9. Italy

Figure 15 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) [33]. 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 [34]. 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 15: Hydrogen pipelines in Italy (modified from https://observatory.clean-hydrogen.europa.eu [5])

Figure 16: Italian hydrogen backbone [36]

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 16, 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 [35].

2.3. Hydrogen liquid distribution grids

This chapter first summarizes ongoing developments of liquid hydrogen distribution networks. Internet research, press releases and project websites served as sources and do not claim to be exhaustive. Also, it might be possible that the status of a given project has changed since the time of this research. Afterwards, metrology for fiscal metering will be enlightened.

2.3.1. Suiso Frontier (Japan)

The "Establishment and demonstration of technologies for a CO_2 free hydrogen energy supply chain comprised of hydrogen production effectively utilizing brown coal, transportation, storage and utilization of hydrogen, to commercialize the supply chain around 2030" is the project content of an association of serval Japanese companies called HySTRA, which stands for "Hydrogen Energy Supply-chain Technology Research Association".

Founded in 2016 by Shell Japan Limited, Iwatani Corporation, Kawasaki Heavy Industries, Ltd. and Electric power Development Co., Ltd. the association wants to establish the world's first commercial hydrogen supply chain.

The chain starts in the Latrobe Valley, Victoria, Australia. In the power plant AGL Loy Yang hydrogen is generated from brown coal gasification. The capacity of the Plant is 100 m^3/h (standard conditions). During the pilot phase CO_2 certificates were bought; but for the commercial phase CO_2 capturing and storing techniques will be applied. The so produced hydrogen gets compressed and then transported via trailer truck to the port of Hastings 150 km away from the power plant where it gets liquified.

The heart of the project is the carrier ship Suiso Frontier (Figure 17). "Suiso" is Japan for Hydrogen. The ship was built by Kawasaki Heavy Industries using existing technologies of LNG marine carriers and for land transportation and storage of liquified hydrogen to develop a new vacuum insulated double-walled tank with a capacity of 1250 m^3 for transporting specifically liquified hydrogen with cryogenic temperatures and accumulated pressure. The Boil-off Rate (BOR), which represents the rate of liquid that evaporates in a day due to natural heat ingress from the outside, is 0.3 % for the Suiso Frontier onboard storage tank and 0.06 % for the Hy touch Kobe onshore storage tank.

After its journey of around 9000 km the freighter reaches the pilot project's unloading site which is located on a 10 000 m^2 area of land in the northeast section of Kobe Airport Island in the Port of Kobe, where the liquefied hydrogen storage tank and unloading facilities were built.

At the beginning of 2022, Suiso Frontier made its maiden voyage and returned to the Liquified Hydrogen Receiving Terminal "Hy touch Kobe" on February 25. Data gained in this process is evaluated and used in further development on the way to guarantee a safe delivery and commercial operation by 2030 [37].

Figure 17: liquid hydrogen carrier Suiso Frontier on its maiden voyage [38]

2.3.2. Kawasaki Heavy vessel

In the meantime, Kawasaki Heavy designed a vessel with a storage capacity of 160 000 m^3, which is 128 times Suiso Frontier's capacity and comparable to LNG carriers (Figure 18). The design already received approval from the Japanese shipping classification society ClassNK. A new dual-fuel combustion engine could use the boil-off hydrogen as well as traditional bunker oil [39].

Figure 18: Kawasaki Heavy's concept hydrogen carrier [39]

2.3.3. Project Aurora (Norway) [Terminated]

"Aurora is the first initiative in Europe that aims to build a complete value chain producing and using green liquid hydrogen for maritime shipping applications. Liquid hydrogen has a tremendous potential to help decarbonize maritime transport and become a zero-emission alternative for shipping", says Lars Strandberg, Vice President Hydrogen Energy Europe Industries of Air Liquide in a press announcement in April 2021 [40].

The Aurora project was a cooperation with BKK, Air Liquide and Equinor to build a complete liquid hydrogen supply chain for the maritime industry. This started with a liquid hydrogen production facility at Mongstad, in Norway, close to an Equinor refinery which produces LH2 from electrolysis and could deliver up to 6 tons of renewable LH2 per day. This was estimated to cover the LH2 needs across western Norway in 2024 - 2026, while paving the way to scaling up production for additional demand. The Aurora project aimed to make liquid hydrogen available for commercial shipping by early 2024.

In March 2023 Equinor announced the termination of the Aurora project, due to failure to attract sufficient purchases of green liquid hydrogen, which was due to its high price according to an Eviny press release. More reasons can be seen in the maritime industry's preference for methanol or ammonia as a carbon-emission reduced fuel instead of pure hydrogen [41].

2.3.4. LH2 Europe

On the website *lh2europe.com,* a concept of a hydrogen tanker ship is presented that carries liquified hydrogen produced in Scotland from renewable sources to Germany and Denmark. The project team of LH2 Europe aims to "have a full liquid hydrogen supply chain ready by 2027," says Dr. Peter Wells, CEO of LH2 Europe. Starting with 100 tons of delivered green hydrogen per day the team wants to ramp up production to 300 tons per day within three years depending on the demand. The plan is to have the ship ready and commissioned six months before the first delivery of hydrogen in 2027 [42].

The initial design of the liquid hydrogen tanker (Figure 19) was created by C-Job. The tanker features three liquid hydrogen tanks, each with a capacity of 12 500 m^3. The total capacity of 37 500m^3 will provide fuel for 400 000 cars or 20 000 heavy trucks in a single voyage. Liquid hydrogen provides unique challenges in ship design and engineering. As it is large in volume but 20 times lighter than LNG, C-Job developed a unique trapezium-shaped hull design which creates enough deck space to fit the tanks without the need for ballast. The overall length of the tanker is 141.75 m and reaches a speed of 14 knots (26 km/h) using its 5 MW fuel cell engine and using the boil-off hydrogen [43].

Figure 192: Illustration of the liquid hydrogen tanker by LH2 Europe [43].

Green hydrogen shall be produced in Scotland from renewable electricity and delivered to the German road transport market at a highly competitive price. The strategic vision is to expand supply to other markets as demand increases. Apart from maintaining the existing zero rating for fuel tax, the project does not require any subsidy to be commercially viable [42].

LH2 Europe CEO Peter Wells arguments choosing liquified hydrogen as a medium: "It is much cheaper than ammonia when you look at the whole cycle of putting the hydrogen into the ammonia and taking the hydrogen out. If you can have liquid hydrogen which is stored without loss or very low loss, then liquid hydrogen is the best option", Wells said at the Offshore Energy Exhibition & Conference in 2022 (OEEC2022) and presented figures showing the aimed pricing (Figure 20). One technical information could be found estimating the boil-off-rate with 0.02 %. This is due to the use of double-wall vacuum insulated tanks while typically in the maritime industry non-vacuum tanks are having 1 % to 5 % boil-off-rate [39].

Wells noted that liquid hydrogen is a better option than ammonia in terms of economics and safety issues; indeed, due to its toxicity, ammonia must be handled in special ports and any leakage into the environment is highly problematic; and although hydrogen is not without safety issues, it has the advantage of not being toxic [44].

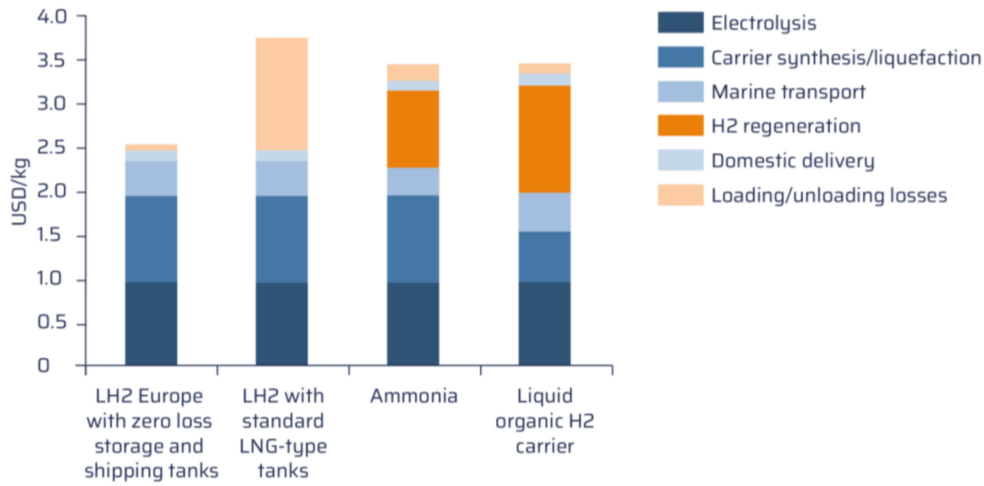

Figure 20: The aimed pricing of LH2 Europe delivered liquid hydrogen [45].

2.3.5. HySHIP

The HyShip project is a collaboration of 14 European partners working on the design and construction of a ro-ro (roll-on/roll-off) demonstration vessel powered by liquid hydrogen. The project started 2021 funded with EUR 8 mil. from the EU's Research and Innovation program Horizon 2020 under the Fuel Cells and Hydrogen Joint Undertaking (FCH2 JU). The project not only aims at designing a new hydrogen powered vessel with the concept name "Topeka", it also aims to establish a viable LH2 supply chain and bunkering platform. The vessel will cover two tasks: carrying coastwise customer cargo along Norway's west coast on a fixed schedule and thus representing a heavy-duty transport route; and also transporting containerized LH2 to so-called bunkering hubs along the Norwegian coast from which LH2 powered vehicles can be operated including local ferries, land transport and seagoing tonnage. The project should validate in large-scale the ship and its innovative propulsion system, and the LH2 distribution network [46].

The ships (Figure 21) will be built and operated by the company Topeka owned by the Norwegian maritime industry group Wilhelmsen. Vice president for special projects at Wilhelmsen Per Brinchmann sees Topeka to be a first step towards scalable LH2 fueled maritime operations which is also Wilhelmsen's way to be in front when shaping the maritime industry to zero emission technology. Two vessels will be built also with funding by the Norwegian government. They have the capacity of shifting cargo transport of 25 000 trucks onto a zero-emission maritime transport. They were expected to be operational in 2024 [46].

Figure 21: Illustration of Wilhelmsen's Topeka vessel [47]

2.3.6. H2Sines.Rdam

H2Sines.Rdam was a project among the energy companies Shell New Energies NL BV, ENGIE, Vopak and Anthony Veder to study the feasibility of producing, liquifying and transporting big amounts of green hydrogen from Sines, Portugal to the Port of Rotterdam, Netherlands [48] (Figure 22). This maritime supply chain for renewable liquid hydrogen produced by electrolysis could provide up to 100 tons LH2 per day to the Dutch and the German markets, keeping e.g. truck applications by Daimler Truck AG in mind. The project has been scrapped before the signing of the final grant agreement in 2023. In a time where clear regulations and infrastructure lacked and the situation of the target market was not clear, the consortium partners concluded that it would not be economically viable [49].

Figure 22: Courtesy of Port of Rotterdam Authority [50]

3. Flow metering technologies

3.1. Gas hydrogen flow metering technologies

Classic technologies used in current gas meters that are used to measure the amount of natural gas flow are expected to be used to measure hydrogen gas as well. 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.

A number of projects have already examined the effect of hydrogen on the upcoming technologies used in classic gas meters, or the effect of a mixture of natural gas and hydrogen on these technologies has been investigated. The results of these projects are summarized in the following sections.

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

In the report [51], 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.

3.1.2. Results of project 18NRM06 NEWGASMET

The 18NRM06 NEWGASMET project [52] aims to enhance understanding of how accurate and durable commercially available gas meters remain when subjected to renewable gases such as biogas, biomethane, hydrogen, syngas, and their blends with natural gas [52].

During this project static tests 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 static durability tests with hydrogen

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 static durability tests with hydrogen

A higher variation was noted in the error shifts of diaphragm gas meters. Prior to undergoing durability testing with hydrogen, all thermal mass gas meters tested remained within the original Maximum Permissible Error (MPE) limits for accuracy class 1.5 gas meters. After the hydrogen durability tests, all of these thermal mass meters still met the tolerance level, staying within twice the initial MPE defined for the same accuracy class [52]. The maximum difference was 1.15 %.

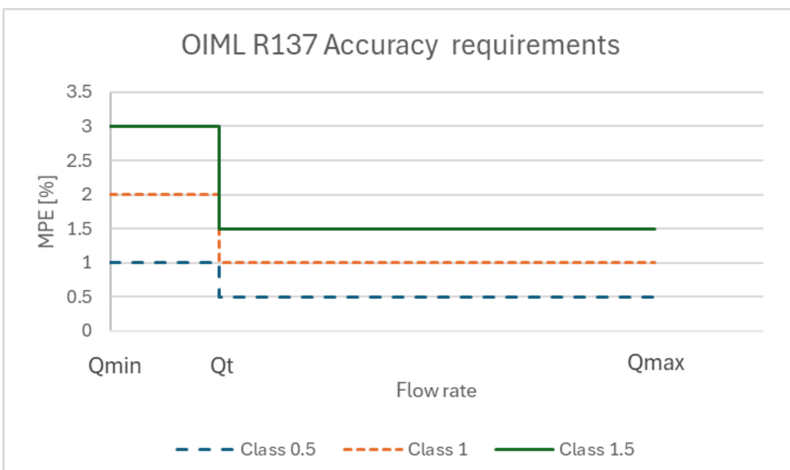

Figure 23: A summary of Maximum Permissible Error (MPE) as a function of flow rate (volumetric or mass), visualizing the different accuracy classes and the terms Q_{min}, Q_t and Q_{max}.

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 23) 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. The results show that, for the rotary flow meter and hydrogen blends containing less than 20 % H_2, the difference in meter error between calibration with high-pressure hydrogen mixtures and high-pressure natural gas is smaller than the difference observed between calibration with atmospheric pressure air and high-pressure natural gas [52].

3.1.3. 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 [53]. 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.

3.1.4. 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 [54].

The experiments were conducted using 2E natural gas as well as blends of natural gas with hydrogen added at volume concentrations of 5 percent, 10 percent, and 15 percent. These tests were performed over durations of 5000 hours and 10000 hours. In some cases, diaphragm gas meters were examined for as long as 15000 hours, while testing of thermal gas meters concluded after 7500 hours. The main conclusions drawn from the results are presented below [54]:

- For all samples tested for durability, including both new gas meters and those that had been in operation for ten years, the presence of hydrogen in the gas mixture did not produce a significant metrological effect on the average drift in measurement error observed after testing. An exception was noted in one Type 1 gas meter from the 2E H0 sample group (without hydrogen), where internal leakage likely occurred. Aside from this case, all meters fulfilled the metrological standards for durability tests as specified by the EN 1359 standard.
- In most instances, neither diaphragm gas meters nor thermal gas meters exhibited any statistically significant change in error due to the presence of hydrogen in the gas after being subjected to long-term testing. However, for new Type 4 diaphragm meters and in-service Type 7 meters, statistically significant differences in the average drift of indication errors were found after 10000 hours of testing when comparing meters exposed to a 2E gas mixture with 15 percent hydrogen to those tested with pure 2E gas. These differences were identified at flow rates of 0.4 times Q_{max}, 0.7 times Q_{max}, three times Q_{min}, and Q_{max}. Nevertheless, a comparison of the average error drift for the control group 2E H0 and the test group 2E H15 shows that the observed variations are smaller than the uncertainty of determining such differences, meaning they should not be considered metrologically significant.
- After 10000 hours of durability testing, no meaningful difference in the average change in weighted mean error was identified across the tested gas mixtures for any meter type. Nearly all measurement errors stayed within a range of plus or minus 1.2 percent, except for four outliers among the 105 tested meters.
- No mechanical failures were discovered during the tests that could jeopardize operational safety. All the gas meters, whether diaphragm type or thermal type, remained leak-proof and structurally intact throughout the testing period.
- The results of tests on diaphragm gas meters, both new and previously used, as well as thermal gas meters, indicate that these devices can be employed for billing purposes when

measuring natural gas containing up to 15 percent hydrogen by volume. However, it is important to emphasize that continued research in flow metrology is necessary, since the results apply only to a specific selection of gas meters and do not represent all designs currently in use.

3.1.5. Summary of gas hydrogen metering technologies

Different gas flow meter technologies have been tested with various gases, but not all of them have been tested with pure hydrogen. For some gas meter technologies predictive models for hydrogen are given, but the extensive experimental validation of these models is still missing.

- The critical flow venturi nozzles have been tested with various gases, where air, nitrogen and hydrogen showed similar behaviour for the relative deviations in the same Reynolds number range. An extrapolation model has been presented, but the experimental validation has only been performed with natural gas. Tests with hydrogen were performed in the project MetHyInfra, but only in the laminar boundary layer regime [62]. Tests in the turbulent boundary layer regime will be performed in this project.
- Turbine meters have been investigated with blends up to 30 % of hydrogen in natural gas. A predictive model for meter deviation with hydrogen exists but is has not yet been validated with hydrogen measurements.
- For the rotary meter a predictive model also exists, but measurements have only been performed with natural gas so far. Measurements with HENG have been performed in the framework of the project NEWGASMET [52]. Measurements with hydrogen are still missing.
- Differential pressure meters have only been tested with natural gas. Measurements with hydrogen are still missing.
- Ultrasonic meters have been investigated with blends up to 30 % of hydrogen in natural gas. Measurements with hydrogen are still missing.
- Coriolis flow meters have been investigated with natural gas. There is very limited data on Coriolis meters used with hydrogen.
- Thermal gas flow meters have been tested with various gases including hydrogen, but the predictive models do not match the experimental results with the necessary accuracy.

Extensive experimental validation of the existing models for the different gas meter technologies are still missing. Therefore, the assessment whether models for air or natural gas can correctly model hydrogen flow is not possible at this stage due to lack of experimental data. A wide range of datasets is needed to estimate the limitations and expected uncertainties of the models.

It is expected that with the upcoming projects related to hydrogen this issue will be covered in the near future.

3.2. Liquid hydrogen flow metering technologies

At the time of writing of this report, no calibration facility was available to provide traceable calibration using LH2 as a calibration medium. What is typically done in flow measurement is to provide traceability by using other calibration fluids, in order to, for example, lower costs or increase safety. It is therefore important to know the introduced error and impacts on the measurement uncertainty when using substitute fluids with differing process parameters other than the target fluid. In the case of cryogenic fluids like LNG or LH2 it might be possible to perform the calibration using liquified nitrogen (LIN), which is a safe, non-explosive fluid, as proxy for an accurate calibration result on LNG or LH2. Due to the lack of traceable primary standards, calibrations are often performed with water which, generically speaking, introduces systematic errors due to the very different fluid properties and process conditions. Metrology for LNG was developed in the last one-and-a-half decades (like in the research projects under the EURAMET EMRP and EMPIR programs LNG ENG03 [55], LNG II ENG60 [56], LNG III 16ENG09 [57]) and has to deal with similar difficulties, so it is worth looking at those achievements first and then looking at the current status in LH2 metrology.

3.2.1. Metrology for LNG

LNG custody transfer measurements at large terminals rely on ship tank level gauging and calibration tables, which are combined with density and LNG composition measurements to compute the amount of transferred energy. From the volume and density measurement, it is also possible to determine the delivered LNG mass (LNG dispensing scale). Another option is to measure the flow when custody transfer takes place, such as when loading/unloading large carriers, fueling an LNG truck, or in LNG ship bunkering. Typical instruments used in the second method are ultrasonic flow meters (USM) and Coriolis Mass Flow (CMF) meters. Due to the lack of cryogenic calibration facilities, these meters are generally calibrated with water and implement mathematical corrections to account for temperature effects at cryogenic conditions. These, however, are based on interpolations or extrapolations. Hence confidence in LNG flow metering can only be established through traceable calibrations at cryogenic conditions [58].

In 2019, VSL completed the construction of the Cryogenic Research and Calibration facility to enable traceable cryogenic flow meter calibrations with a target maximum flow rate of 200 m^3/h and a target measurement uncertainty of 0.15 % in mass flow rate. The facility contains the Primary Standard Loop (PSL) which was built in 2013 and gives traceability for mass flow by a gravimetric weighing principle. The PSL is used to calibrate the working standards of the mid-scale Loop (MSL) which allows the calibration of a meter-under-test in a closed-loop method. The sub-cooling of the cryogenic fluid is important for good results as it stabilizes the liquid phase and prevents bubbles or cavitation in the flow. This can be achieved by increasing the pressure and consequently shifting its boiling point above the fluid's temperature. Within the EMPIR projects ENG60 LNGII and 16ENG09 LNGIII, the facility was commissioned in 2019 with LIN (liquid nitrogen) as cryogenic fluid, having next the objective to be used with LNG [59], [60].

Within the scope of the projects the facility was used to assess the three main objectives [61]:

- reducing the onsite flow measurement uncertainty for small and mid-scale LNG applications to meet a target measurement uncertainty of 0.50 % (k = 2).

- assessing the impact of upstream flow disturbances and meter insulation on meter performance.
- assessing transferability of meter calibrations with water at ambient conditions to cryogenic conditions.

The results indicate that:

- The corrections used to transfer the water calibration to LIN conditions resulted in meter errors, for the ideal case, within ±0.50 % for about 85 % of the results. A target measurement uncertainty of 0.50 % (k = 2) can be achieved if the standard error of the mean value of each calibration point is lower than 0.40 % (k = 2) as the combined measurement uncertainty of the cryogenic facility using LIN is 0.30 % (k = 2).
- Flow disturbances do not affect measurement accuracy much if a straight piping equivalent to 20 times the pipe diameters is installed upstream the meter.
- Proper insulation of the meter is very important and can lead to errors higher than ±0.50 % if not done correctly.

It should be noted that these results are based on tests using LIN as a cryogenic fluid. LIN has a boiling point of -196 °C which is 35 K lower than for LNG.

3.2.2. Metrology for LH2

Within the Joint Research Project (JRP) 20IND11 "Metrology infrastructure for high-pressure gas and liquified hydrogen flows" (MetHyInfra) [62] traceability of both high-pressure gaseous as well as liquified hydrogen was investigated. SI-traceable measurement of liquified hydrogen (LH2) flows was investigated by different approaches:

a) Calibration results with alternative fluids:

In a comparison presented in [63] and [64], calibrations of two flow meters intended for the use with liquified hydrogen were carried out with water and LNG as calibration fluid in VSL's traceable calibration facilities. One was a 2" turbine type flow meter, the other a 2" Coriolis mass flow meter (CMF). The calibration result for the CMF is shown in Figure 24. While the water calibration was at an error of around 0.0 %, the LNG calibration was at an error of around -0.4 % indicating that there might be a systematic shift between water and LNG calibrations. The expanded uncertainty was 0.10 % for water and 0.18 % for LNG. The CMF was insulated during the LNG test. The results of the turbine meter calibrations are shown in Figure 25 in terms of the Reynolds number which is commonly believed to describe the meter behaviour. Again, an indication of a systematic shift is observed as the K-factor was at about 64 for water but was about 61 to 64 on LNG varying with Reynolds numbers. Therefore, when extrapolating alternative fluid calibrations to LH2 cryogenic conditions additional errors could arise that were not discovered during an alternative fluid calibration.

A further calibration result of another CMF is presented in [65]. It was calibrated using water and LNG. The results are shown in Figure 26 and show similar behaviour to the CMF shown above.

It is further discussed that for a calibration in OIML R117 accuracy class 1.5 %, implying a maximum permissible error (MPE) of 1.0 % for the meter, an uncertainty of one fifth (for type approvals) or one third (for verifications) is required [63]. Keeping in mind the LNG calibration uncertainty at about 0.2 % (k = 2), and the need to extrapolate from LNG (-162 °C) to LH2 conditions (-253 °C), delivering LH2 measurement uncertainty at a 0.2 % uncertainty (k = 2), will therefore be very challenging when relying on an LNG or LIN calibration.

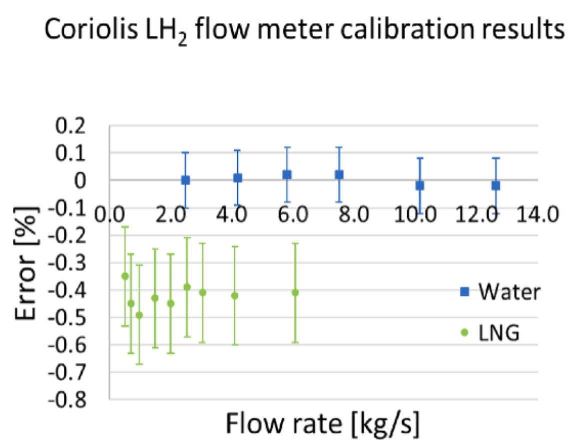

Figure 24: CMF alternative fluid calibration results obtained in VSL's traceable calibration facilities. Calibration uncertainty is indicated by the error bars (uncertainty, k = 2). Reprocessed from [63] with slight modification to the title.

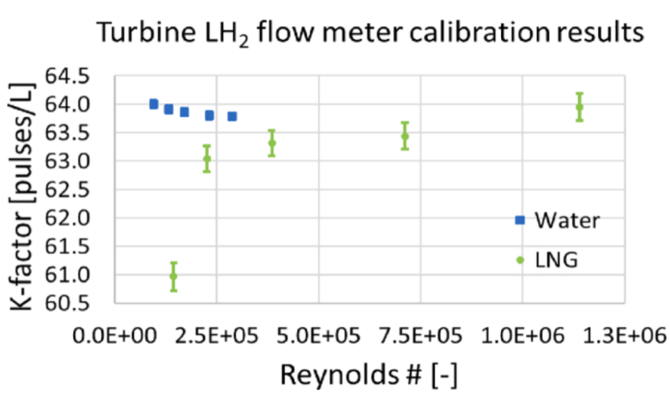

Figure 25: LH2 turbine flow meter alternative fluid calibration results obtained in VSL's traceable calibration facilities. Calibration uncertainty is indicated by the error bars (uncertainty, k = 2). For the water calibration, these bars are smaller than the symbols. Reprocessed from [63] with slight modification to the title.

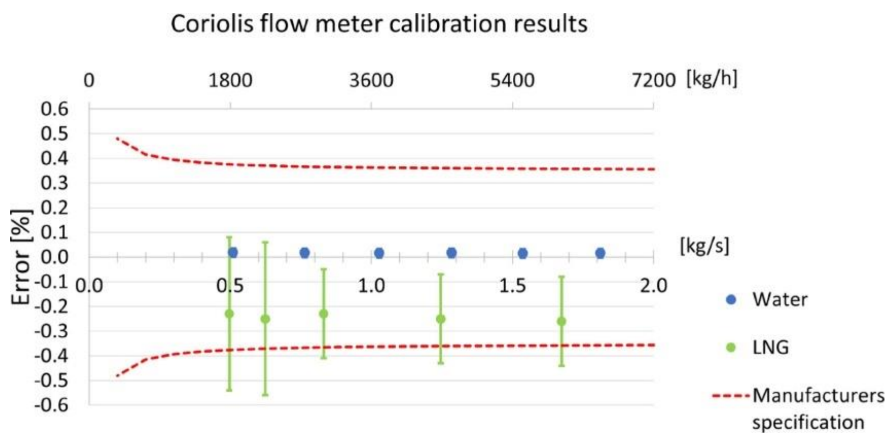

Figure 26: LH2 CMF100 calibration results using water and LNG as alternative calibration fluids. Water calibration results are obtained from Emerson's ISO/IEC 17025 accredited calibration laboratory. LNG results are obtained in VSL's SI-traceable calibration facility. Calibration uncertainty is indicated by the error (uncertainty, k = 2) bars (water uncertainty is small with respect to the symbol size). Reprinted from [65].

b) Assessment of transferability of water and LNG calibrations to LH2 conditions:

Since Coriolis mass flow meters (CMF) but also turbine flow meters rely on mechanical (moving) parts, a temperature dependence of the flow sensitivity factor is expected. Temperature has an impact on elastic material properties and induces thermal strain and thermal stress. Although temperature correction models do exist, it was in the focus of the investigation to predict to what extent these correction models can be extrapolated and be used at cryogenic LH2 conditions (20 K). First, analytical models for CMFs were developed based on physical parameters like the Young's modulus and the Poisson's ratio. It is necessary to point out that there is not a single model describing all types of CMFs (straight-tube, U-tube, arc-tube). For example, the Poisson's ratio has significantly more impact on the U-type CMF than on the straight-tube CMF. The models were developed to predict the uncertainty budget of a CMF at cryogenic LH2 conditions if the calibration is carried out under ambient conditions. The models include uncertainties of the physical parameters but here the limited availability of datasets of material properties (stainless steel 304, 310, 316) was found to be challenging but also that the uncertainty of the literature data in some cases is not reported according to currently applicable standards (e.g., the GUM [66]). In the next step finite-element-modelling (FEM) was applied to the models of the straight-tube, U-shaped and arc-shaped CMF designs to evaluate the analytical temperature correction models by contrasting the analytical model predictions with a FEM reference. For curved tube designs (U-tube and arc-shape) the flow sensitivity was calculated to be about 6 % to 7 % lower at LH2 temperature of 20 K than at ambient temperature and by about 25 % for the straight tube design. The FEM models were then used as a reference in a comparison to the analytical temperature correction models. The applicability of these correction models could so be evaluated. For the curved tube geometries, the results show good agreements (0.03 % for the U-tube and 0.11 % for the arc tube) for a correction model considering the effects of Young's modulus and thermal strain (using experimental data for the temperature dependence of these material properties) as well as the effect of the Poisson's ratio (estimated from a flow calibration close to ambient conditions). It is concluded that the curved-tube meters, especially the U-tube, offer greater potential for accurate measurements under extreme cryogenic conditions, as they are less susceptible to the potential effects of internal thermal stresses. For straight-tube meters it was found that the correction model also applies well but that differences between the thermal strain of the measuring tube and its clamping part can lead to large thermal stresses which are not adequately covered by the temperature correction model, resulting in significant prediction errors [62], [64], [67].

Alternative fluid calibrations of a CMF were performed using water and LNG which were shown above [65] (Figure 27). These were combined with analytical meter models and corresponding uncertainty evaluations for an on-site LH2 flow calibration of two turbine meters at relatively large flow rates (1000 kg/h to 3000 kg/h). From the alternative fluid calibration and the uncertainty evaluation, the authors estimate traceable liquefied hydrogen flow measurement uncertainty and find an indication that it lies within a range of 0.4 % to 1.0 % (k = 2) relative to mass flow rate range. They also find errors of the turbine meters ranging from 2.0 % to 2.9 % with a total calibration uncertainty of 1.3 % (k = 2), which is dominated by the LH2 onsite density determination. They conclude with stating that further proving of LH2 flow calibration uncertainties is needed to substantiate findings.

c) Cryogenic Laser Doppler Velocimetry (LDV) adapted to LH2 flow applications:

Cesame–Exadebit, as the designated institute of the LNE for high-pressure, monophasic gas flow measuring, established the technique of Laser Doppler Velocimetry (LDV) as a primary standard for cryogenic flow meters in the last one-and-a half decade. The standard allows to perform online calibration of cryogenic flow meters under real cryogenic conditions (temperature, pressure, piping and real flow disturbances) while traceability is given by length (fringe spacing) and time measurements (Doppler frequency). The standard is mobile and does not introduce downtime to the truck operations when being installed in field e.g. between an LNG terminal and an LNG truck. The uncertainty was estimated to be 0.6 % (k = 2), for a liquid nitrogen calibration under laboratory conditions at NIST [68]. As the development of the standard first targeted traceable calibrations of LNG some modifications needed to be done to enlarge its applicability to LH2 conditions. This was performed in recent years during the MetHyInfra project. The technique looks very promising also to enable LH2 application allowing to be used either as a primary standard or as a secondary standard under industrial process conditions (1000 kg/h to 5000 kg/h and pressures up to 10 bar). The LDV technique requires a monophasic flow (liquid or gas) [69].

d) Assessment of transferability of water, liquefied nitrogen, and liquefied helium calibrations by the vaporization method to LH2 conditions:

This approach vaporizes the cryogenic fluid after it has passed through the meter under test and is brought to ambient temperature. Laminar flow elements then enable the SI-traceability for different flow rates of the gas phase. A facility implementing this measurement principle was built by the Karlsruher Institut für Technologie, Germany. It enables the testing of flow meters using liquified nitrogen (77 K) and liquified helium (4 K) as alternative fluids to the usage with LH2 and so covering the temperature around 20 K. Although the vaporization method could not be performed with liquified helium as planned due to problems of delivering single-phase fluid to the meter it could be successfully tested with liquified nitrogen (LIN) with a reached uncertainty of 2 % and hence the potential of the method was shown [64], [69].

One important aspect has to be considered for LH2: the conversion of para hydrogen to normal hydrogen, which has been studied in detail by Günz et al. [70]. At low temperatures, para hydrogen is the predominant type while at ambient temperatures the ratio changes to 25 % para and 75 % ortho hydrogen (so-called normal hydrogen). As para and ortho hydrogen differ significantly in certain physical properties, such as thermal conductivity, heat capacity or speed of sound, gas flow measurements are directly affected. Even when using a catalyst, it was found that it was difficult to ensure the complete conversion from para to normal hydrogen of vaporized hydrogen. The reason is that conversion needs certain temperatures to take place that were unattainable or difficult to reach. Hence to improve the conversion rate either a high amount of catalyst is needed or low flow rates. Günz et al. give some examples of flow meters that due to their measuring principle are insensitive to the physical parameters affected by the para/ortho composition: These are Coriolis flow meters, differential pressure flow meters, vortex flow meters and mechanical flow meters (like rotary, turbine or diaphragm flow meters), and it is also expected that Ultrasonic flow meters can be used.

3.2.3. Summary of gas hydrogen metering technologies

Metrology for LH2 is developed based upon research for LNG metrology. VSL's LNG calibration facility or CESAME's cryogenic LDV standard open the first possibilities to calibrate meters under cryogenic conditions. Systematic errors between alternative fluid calibrations with water and cryogenic calibrations could be found in the magnitude of 0.4 % for available meter types like Coriolis or Ultrasonic Flow Meters. Temperature correction models were evaluated for LH2 conditions to support meter calibration at ambient conditions while predicting the correction model uncertainty at LH2 conditions. To progress LH2 flow metrology, proving of employed temperature correction models for LH2 flow meters is needed. This in turn requires the development of LH2 flow measurement standards and to undertake calibrations of LH2 flow meters with them.

4. Conclusion

Hydrogen can be assumed to be a clean energy medium in the future, but we are still only at the beginning of its use. Many studies will still need to be conducted regarding the transport and precise measurement of the delivered amount of hydrogen.

This technical report has covered the use of gaseous hydrogen in gas pipelines in Europe, including both the gas distribution network and any specific plans to use the network to transport hydrogen. Pilot projects are currently being implemented or are being prepared, where pure hydrogen will flow and the behaviour of the entire network will be monitored from the point of view of safety and measurement accuracy of the meters used. From the data obtained, it can be expected that diaphragm gas meters would be used to measure gas 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.

There is even less experience in the distribution and measurement of liquid hydrogen than with gaseous hydrogen. The transport of liquid hydrogen is expected to be carried out using large ocean-going ships or trucks that will have special modifications. For now, it can be assumed that Coriolis flow meters will be used to measure the amount of liquid hydrogen.

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.

Since developing modern standards for complex technologies often takes years, it is important to quickly create and follow a clear plan with set priorities. Developing these standards on time is key to keeping them aligned with both new technologies and current laws and regulations. That is why *European Clean Hydrogen Alliance (ECH2A)* [71] and *CEN* issued the ROADMAP ON HYDROGEN STANDARDISATION [72].

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