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Liquid Hydrogen Transport Landscape

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1 INTRODUCTION

The present work provides an overview of the landscape for hydrogen transport, focusing on liquid hydrogen. The work outlines the current regulatory framework in Europe and North America. A summary of the frameworks relevant to accelerating the hydrogen economy is presented, based on the EU Hydrogen strategy, the EU taxonomy, the European Trading System, RePowerEU, and the Departmen of Energy (DOE) National Clean Hydrogen Strategy and Roadmap.

The work summarises various forecasts that try to predict how the economy will evolve, contrasting the European-centred perspective vs global predictions. Recent forecast studies agree that the transport sector will require around 55 Mt of hydrogen by 2050. Of this, the liquid hydrogen use is expected to be about 15 Mt. The demand for liquid hydrogen stems mainly from the need to transport hydrogen long distances from energy-rich sources to demanding economies. Another use for liquid hydrogen is storing large quantities of hydrogen in mobility applications. Such storage needs encompass the refuelling of fuel-cell electric vehicles, barges, or ferries. Within the aviation industry, hybrid-hydrogen aircraft powered by liquid hydrogen will also require hydrogen storage on land and on the aircraft. However, most of the scenarios for a hydrogen economy are very optimistic and rely on ambitious assumptions such as fast readiness, deployment, and acceptability of hydrogen. Yet, current hydrogen market trends lean towards a 'Business as Usual Scenario'.

The realisation of a hydrogen economy presents various challenges that need to be overcome in the immediate future. Advancing hydrogen metrology TRL can help overcome some of such challenges. The most pressing challenges for hydrogen in transport applications and inherent metrology operations are identified.

Although a very limited public bibliography is available, an effort is made to provide a critical overview of the current state of the art and various measurement technologies relevant to the transport of liquid hydrogen, encompassing flow metering and level metering. Finally, a summary of existing and upcoming experimental capabilities with liquid hydrogen or nitrogen to accelerate research and development within Europe is provided

2 REGULATORY FRAMEWORK

2.1 Europe

The view of the EU on hydrogen is that it can be used as a fuel, an energy carrier or a feedstock and could reduce emissions in hard-to-abate sectors, particularly in industry and transport. The EU Hydrogen Strategy [1] looks to harness the business opportunities associated with the production of decarbonised hydrogen. Global interest will mean new opportunities for EU companies, which are being stimulated by the proposals adopted by the Commission today. Some of the frameworks within the EU relevant to the acceleration of the hydrogen economy are summarised below.

2.1.1 EU Taxonomy

It is estimated that the EU's climate plan requires an investment of €2.6×10^{12} by 2030. Of this, the EU has mobilised between 2020-2030, just under 40%. To cover the remaining deficit private financing is key. The EU taxonomy, adopted in 2021, aims to encourage financing prioritisation towards sustainable businesses.

The EU Taxonomy is a classification framework to determine whether an economic activity is environmentally sustainable. It was created to help companies and investors identify environmentally sustainable economic activities so that sustainable investment decisions are made. An environmentally sustainable economic activity should meet three criteria, namely (i) make a substantial contribution to at least one of the EU's climate and environmental objectives, i.e., (1) climate change mitigation, (2) climate change adaption, (3) sustainable use and protection of water and marine resources, (4) transition to a circular economy, (5) pollution prevention and control, and (6) protection and restoration of biodiversity and ecosystems. The latter four objectives were implemented in June 2023. Thus, at this date, the criteria for substantial contributions are mainly defined solely for the former two objectives. (ii) at the same time not significantly harm to any of the other objectives, and (iii) meet minimum safeguards.

The EU Taxonomy has a wide coverage. It encompasses 13 sectors. Of these, the most relevant for the scope of this work are: Energy, Manufacturing, and Transport. A summary of the Taxonomy contribution criteria for sector of interest is in Table 1.

2.1.2. European Emission Trading System (EU ETS)

The EU ETS is a cap-and-trade system, in which a limit on the total amount of certain greenhouse gases that can be emitted by the operators is set and covered by the system. Such a cap is successively reduced over time. The system enables operators to trade the received emissions allowances as needed. The EU ETS includes the production of hydrogen with electrolysers under the EU emissions trading scheme, making renewable and low-carbon facilities eligible for free allowances. Currently, the operators covered by the scheme are stationary installations and the aviation industry. It is proposed that after 2024 large-scale maritime transport will also be covered.

2.1.3. RePowerEU

REPowerEU was launched as a response to the hardships and global energy market disruption caused by the Russian invasion of Ukraine. The REPowerEU plan, which entered into force in May 2022, has the following ambitions for 2030: (i) replace Russian energy import, (ii) increase the total energy generation to 1236 GW, of which 600GW from solar photovoltaic, (iii) increase hydrogen production and import in 10 million tonnes each, and (iv) replace the fossil fuel in heavy industry, for which the steel industry shall have over 30% of hydrogen penetration.

2.1.4. Other legislative proposals in the EU

The Fit-for-55 package put forward legislative proposals to integrate the European hydrogen strategy into a concrete European hydrogen policy framework. This includes (i) proposals to set targets for the uptake of renewable hydrogen in industry and transport by 2030, (ii) the Hydrogen and decarbonised gas market package [2], which proposes supporting the creation of optimum and dedicated infrastructure for hydrogen, as well as an efficient hydrogen market, (iii) two delegated acts [3], one defining under which conditions energy carriers can be considered as renewable fuels of non-biological origin (RFNBOs); the second providing a methodology for calculating life-cycle greenhouse gas emissions for RFNBOs.

Table 1. EU Taxonomy criteria relevant for the hydrogen economy

Sector	Activity	Substantial contribution	Taxonomy contribution Criteria
Energy	Construction and safe operation of new nuclear power plants … including for hydrogen production…	(1) Climate mitigation	Life-cycle GHG emissions from the generation of electricity from nuclear energy < 100 g CO_2e/kWh [link]
Energy	Storage of hydrogen	(2) Climate adaptation	The adaptation solutions implemented, are monitored and measured against pre-defined indicators and remedial action is considered where those indicators are not met [link]
Energy	Transmission and distribution networks for renewable and low-carbon gases	(1) Climate mitigation	Construction or operation of new transmission and distribution networks dedicated to hydrogen or other low-carbon gases; Conversion/repurposing of existing natural gas networks to 100% hydrogen; Retrofit of gas transmission and distribution networks that enables the integration of hydrogen and other low-carbon gases in the network, including any gas transmission or distribution network activity that enables the increase of the blend of hydrogen or other low-carbon gasses in the gas system;
		(2) Climate adaptation	Construction or operation of transmission and distribution pipelines dedicated to the transport of hydrogen and other low-carbon gases [link]
Manufacturing	Manufacture of equipment for the production and use of hydrogen	(2) Climate adaptation	The adaptation solutions implemented, are monitored and measured against pre-defined indicators and remedial action is considered where those indicators are not met [link]
Manufacturing	Manufacture of hydrogen	(1) Climate mitigation	Life-cycle GHG emissions savings: For H_2: 73.4% 3tCO_2e/tH_2 For H_2-based synthetic fuels: 70% relative to a fossil fuel comparator of 94g CO_2e/MJ [link]
Manufacturing	Iron and Steel	(1) Climate mitigation	Iron and Steel: GHG emissions <0,209-1,63tCO_2e/t product Electric Arc furnace: GHG emissions <0,209-0,266tCO_2e/t product [link]
Transport	Infrastructure enabling low-carbon road transport and public transport	(1) Climate mitigation	The infrastructure is dedicated to the operation of vehicles with zero tailpipe CO_2 emissions:… hydrogen fuelling stations [link]
Transport	Infrastructure for personal mobility, cycle logistics	(1) Climate mitigation	The infrastructure that is constructed and operated is dedicated to personal mobility or cycle logistics: … hydrogen refuelling installations for personal mobility devices [link]
Transport	Low-carbon airport infrastructure	(1) Climate mitigation	The infrastructure is dedicated to the operation of aircraft with zero tailpipe CO_2 emissions: electricity charging and hydrogen refuelling. The infrastructure is dedicated to the zero direct emissions performance of the airport's own operations: … hydrogen refuelling stations [link]

2.2 North America

The United States already produces more than 10% of the global hydrogen supply and plays an important role in developing the global hydrogen economy. Against this backdrop, the DOE National Clean Hydrogen Strategy and Roadmap [4], in force since September 2022, establishes $9.5 billion for clean hydrogen initiatives as part of a larger legislation package ($ 62B) authorized by US government in 2021. The targets of such initiative is the production and utilisation of 10 million metric tonnes (MMT) of clean hydrogen annually by 2030, 20 MMT annually by 2040, and 50 MMT annually by 2050.

In June 2021, the DOE launched Hydrogen Shot [5] with a bold and ambitious goal of "1 1 1" – $1 for 1 kilogram of clean hydrogen in 1 decade – to unlock the potential for hydrogen across sectors.

The National Clean Hydrogen Strategy and Roadmap aligns with the Administration's goals, including (i) a 50% to 52% reduction in U.S. GHG emissions from 2005 levels by 2030, (ii) 100% carbon pollution-free electricity by 2035, and (iii) net zero GHG emissions no later than 2050.

The Bipartisan Infrastructure Law (BIL), signed by President Biden in November 2021 puts forward:

- $1 billion for a Clean Hydrogen Electrolysis Program
- $500 million for Clean Hydrogen Manufacturing and Recycling RDD&D Activities
- $8 billion for Regional Clean Hydrogen Hubs
- Clean Hydrogen Production Standard
- National Clean Hydrogen Strategy and Roadmap

3 THE HYDROGEN ECONOMY – A FORECAST

3.1 European-centred perspective

Gondia *et al.* [6] predicted the possible hydrogen-exporting countries in the vicinity of Europe. Depending on the location where hydrogen is produced, onshore transport and logistics might be needed to move hydrogen to an exporting port or to the inlet of an interconnector. For hydrogen sources, the study considered only renewable energy locations within a 1000 km distance around exporting points. This ensures road accessibility to an exporting point. The domestic transport segment was assumed to be covered by trucks (either in compressed or liquid form). For international transport, dedicated hydrogen interconnectors, ammonia shipping, and liquified hydrogen were considered. The resulting landscape is illustrated in Figure 1.

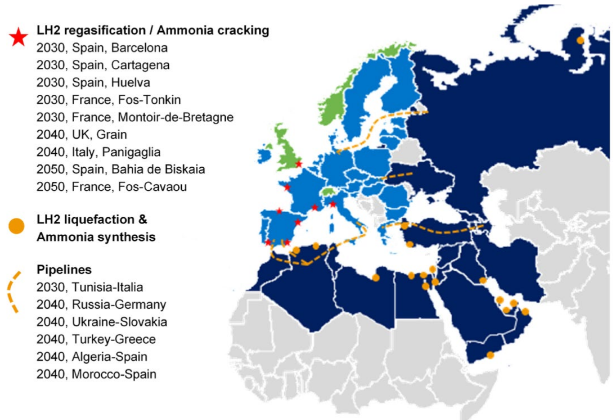


Figure 1. Hydrogen imports to Europe and alternative routes (Source: Gondia et al 2022 [6][1])

The forecast in [6] states that around 55 Mt of hydrogen will be consumed by the transport sector in 2050 (55% of the total hydrogen demand), either in fuel cells to produce e-fuels or in biorefineries for second-generation biofuels. Of such hydrogen demand for e-fuels, aviation alone uses around 20 Mt. Hydrogen demand in the industry will reach around 45 Mt in both scenarios by 2050. About 60% of this industrial hydrogen demand is consumed in heat and steam processes (15% in chemicals and 45% in non-energy intensive industries). The remaining 40%, or about 18 Mt, is consumed as an alternative route for direct reduced iron (DRI) in the iron and steel industry.

The penetration of hydrogen in other sectors like buildings decarbonation, and electricity production is limited (2.2 Mt - 5.1 Mt) due to the competition with other available options, such as renewables (VREs, biogas, BECCS), heat pumps, and continued use of natural gas.

In line with [6] the authors of the Hydrogen4EU 2022 report [7] expect the transport sector to use 51-54 Mt by 2050. The latter report discretises that of this total, 38-46% will be liquified (14-17 Mt). The hydrogen demand more than quadruples over the 2030s, reaching between 66 Mt

[1] Reprinted from Renewable and Sustainable Energy Reviews, vol. 167, Gondia S. et al., Hydrogen and the decarbonization of the energy system in europe in 2050: A detailed model-based analysis, 2020, with permission from Elsevier.

and 75 Mt by 2040. The hydrogen demand stems mostly from industry and transport, two hard-to-abate sectors for which hydrogen's versatility and flexibility prove particularly relevant. In the 2040s, the increase in hydrogen demand slows down, reaching between 99 Mt and 104 Mt by 2050.

Hydrogen fuel cell electric vehicles lead the way for decarbonising buses and heavy-duty trucks due to the higher energy density and lighter fuel reservoir than electric vehicles. It is expected that by 2050, more than 13 million buses and heavy-duty trucks, which constitute 90% of the fleet, will be directly fuelled by hydrogen via fuel cell electric engines. Yet such high penetration is contingent on the timely roll-out of a Europe-wide refuelling infrastructure. The report [7] proposes that risks associated with the commercial viability of such an infrastructure can be mitigated via captive fleets and targeted supply and refilling station along stablished routes.

However, hydrogen's energy density is much lower than that of fossil fuels used in aviation; direct use of hydrogen in aircraft should, therefore, remain limited due to the complexity of storing large amounts of hydrogen fuel. Direct use of hydrogen in fuel cells is promising for short trips (e.g., for barges or ferries). Long-distance journeys would require fuel with a higher energy density, relying on liquefied hydrogen or ammonia. ZEROe project from Airbus, looks into three concepts of hybrid-hydrogen aircraft powered by liquid hydrogen [8].

3.2 The European vs the Global perspective

Both 'A Clean Planet for All' by the European Commission-2018 and the 'Hydrogen Roadmap Europe' by FCH-JU have similar views on Hydrogen as reported in [9]. They are both very optimistic and rely on very ambitious hypotheses, such as a very fast readiness and deployment and acceptability of hydrogen. Thus, with the current trends of the hydrogen market, the 'Business as Usual Scenario' seems more realistic than other more expedite-development scenarios suggested in [9].

The global perspective from the Hydrogen Council for sectorial repartition of hydrogen is somewhat different from the European ones above. Two sectors seem to benefit the most from the development of a hydrogen economy, i.e., industry (45 % of the final energy demand in H_2) and transportation (30 %). This is explained by Reigstad et al, [9] by the fact that, from a global perspective, industrial production is mainly located outside Europe. However, the overall Hydrogen development is the same as for Europe: a slow start until 2030, followed by a massive adoption by 2050.

4 CURRENT HYDROGEN LANDSCAPE

According to the IEA [10], by 2019, the hydrogen used worldwide amounted to 115 Mt/year (see Figure 2). The main applications for the produced hydrogen are oil refining and ammonia production, mainly for fertilisers, which take up 60% of the hydrogen market. A further 45 Mt (39%) of the hydrogen demand is as part of a mixture of gases, such as synthesis gas, for fuel or feedstock for methanol production and steel production.

Overall, one-third of the hydrogen demand today is for transport sector applications in a broad sense, i.e., in refineries and for methanol used in vehicle fuel. Yet less than 0.01 Mt per year of pure hydrogen is used in Fuel Cell Electric vehicles (FCEV).

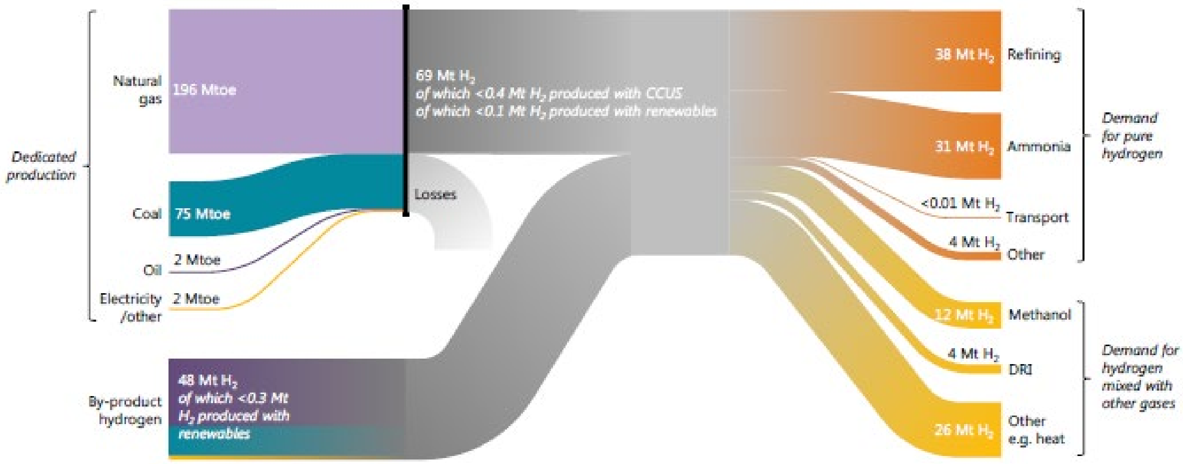


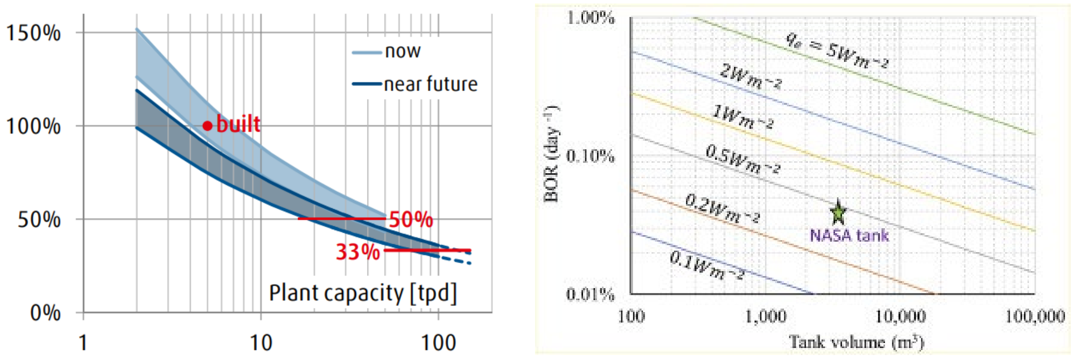
Figure 2. Current use of Hydrogen (Source: IEA, 2019, Today's hydrogen value chain, Fif 6, p32 [10])

4.1 Economy of scale in Liquid hydrogen transport and storage

The effect of economic benefits attained by increased scale is well known to numerous industrial process; Liquid Hydrogen (LH_2) is no exception. The cost efficiency of LH_2 depends on upscaling the amounts of hydrogen, which entitles larger liquefaction plants and storage tanks.

In this sense, the efficiency and relative costs of LH_2, production, transport, and storage largely depend on the scale. For example, as evident in Figure 3 (a) from [11], the cost of liquefaction can be reduced by 50 to 70% when liquefaction plants are scaled up from a few t/ day to 100t/d. This is for a cost of 0.05 €/kWh and 20 years depreciation, and disregarding land costs and feed compression cost.

For storage of LH_2, the work in [12] shows that the relative boil-off decreases with larger tank sizes, for a fixed heat flux, (see Figure 3 (b))



(a) (b)

Figure 3. (a) Reduction in liquefaction cost (ordinate) with increasing plant capacity (abscissa) *(Source: L. Deker [11][2]) (b)* Boil-off rate versus tank size for a fixed insulation thickness (Source: Ratnakar, R. et al, [12][3])

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[2] Reprinted from HYPER closing seminar. L. Decker, Liquid hydrogen distribution technology", 2019, with permission from the author.

[3] Reprinted from International Journal of Hydrogen Energy vol. 46, R. Ratnakar et al., Hydrogen supply chain and challenges in large-scale LH2 storage and transportation, 2021, with permission from Elsevier.

4.2 The Hydrogen value chain

Feedstock for the production of hydrogen includes natural gas, oil, coal, and water. Hydrogen can be produced by numerous technologies such as methane reforming with CCS, methane pyrolysis, dedicated off-grid wind, Photovoltaic (PV) or wind + PV hybrid systems with electrolysers (location dependent), and biomass gasification, each leading to different production costs [6].

Hydrogen production can be centralised or decentralised depending on the location of the feedstock and the end users. In the decentralised scenario, hydrogen is produced close to where it is consumed, whereas, in centralised production, large-scale hydrogen facilities produce hydrogen that needs to be delivered to end-users via an extensive transport and distribution infrastructure.

Figure 4 illustrates the typical hydrogen value chain. Depending on the context various components can be combined in value chains for hydrogen transmission and distribution, including incorporation of the hydrogen into larger molecules. Different pathways for hydrogen transport involve compression, transmission, blend, liquefaction, road transport, ship transport, intermediate storage, distribution pipelines, and refuelling stations. Not all combinations among these are possible (e.g. liquefaction and injection to the grid). Blanco *et al.* [13] identified 20 delivery chains. Each option has pros and cons, and economics vary according to geography, distance, scale and the required end-use [6].

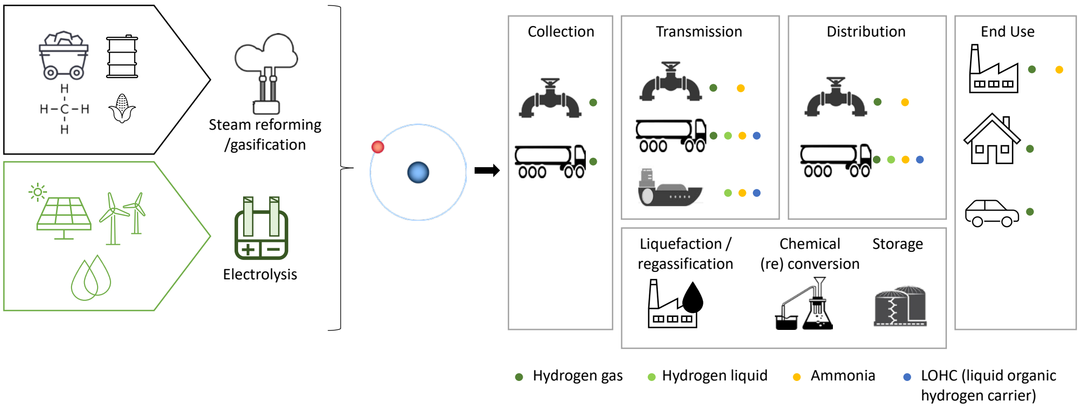


Figure 4. Hydrogen value chain

4.3 Hydrogen transport

For long-distance transport, hydrogen needs to be liquefied or transported as ammonia or in liquid organic hydrogen carriers (LOHCs). The IEA estimations indicate that for distances below 1500 km, transporting hydrogen as a gas by pipeline is likely to be the cheapest delivery option; above 1500 km, shipping hydrogen as ammonia or a LOHC is likely to be more cost-effective. However, the costs of conversion before export and reconversion back to hydrogen before consumption are significant. Further, issues related to safety and public acceptance issues, must be taken into consideration.

Pipelines are likely to be the most cost-effective long-term choice for local hydrogen distribution if there is sufficiently large, sustained, and localised demand. Most natural gas and oil are moved around the world in large-scale pipelines and ships, and both options can also be used for hydrogen and hydrogen carriers. Moving hydrogen using trains could also be an inland option for some regions, although this would, in general, be a more expensive option than moving the hydrogen by pipeline.

Distribution today usually relies on **trucks** carrying hydrogen either as a gas or liquid. The IEA estimates that trucks are likely to remain the main distribution mechanism over the next decade. Distribution via trucks is done as compressed gas trailers for distances less than 300 km. Liquid hydrogen tanker trucks are often used instead where there is reliable demand, and the liquefaction costs can be offset by the lower unit costs of hydrogen transport. In both cases, the hydrogen is distributed in tubes that are loaded onto trailers. Highly insulated cryogenic tanker trucks can carry up to 4000 kg of liquefied hydrogen and are commonly used today for long journeys of up to 4000 km. Above 4000 km, the hydrogen heats up and causes a rise in pressure.

Ammonia, on the other hand, is often transported by pipeline, and new pipelines for ammonia would be cheaper than new pipelines for pure hydrogen. LOHCs are similar to crude oil and diesel, and so could use existing oil pipelines. However, the need to transfer the hydrogen carrier back to its place of origin to be re-loaded with hydrogen, either by truck or a parallel pipeline operating in the opposite direction, makes this a complicated and expensive method of transport.

Trucks can also be used to distribute ammonia or LOHCs in a broadly similar way to hydrogen. Around 5000 kgH_2 in the form of ammonia or 1700 kgH_2 in the form of LOHC could be moved in a road tanker. In the case of LOHC, a truck would also be needed to transport the carrier molecules back to their original destination after the hydrogen has been extracted from them.

Hydrogen **shipping** has gained increasing traction in the past years. In 2020 the Suiso Frontier became the world's first liquefied hydrogen carrier. This first-of-a-kind carrier combined existing technologies available for LNG marine transport and for land transport and storage of LH_2. The ship was used in the Hydrogen Energy Supply Chain (HESC) Pilot Project completed in February 2022. HESC demonstrated the technical feasibility of shipping liquefied hydrogen from Australia to Japan. The total capacity of the pilot was 89 ton LH2 or 3 GWh [14]. In 2023 the project entered the commercial demonstration phase aiming to supply 30,000 t LH2/y by 2030.

Currently the transport capacity of LH_2 cargo is smaller than for LNG (0.5-1.2TWh), but upscaling is expected. Further advances in LH_2 shipping aim to build cargo with capacity to transport 10,000 LH2 by 2030 [15] .

4.3.1 Biggest challenges

The working paper from HySupply [16] summarises the main challenges of Liquid Hydrogen transport as:

a) Cryogenic temperatures: Infrastructure must be fitted for handling cryogenic conditions and minimise boil-off losses.
b) Uncertainty: Low TRL yields high uncertainty. Only one small-scale demonstration vessel is in operation, and one technology provider is involved; thus, the availability of sufficient large-scale vessels by 2030 is uncertain.
c) Intermittency: Liquefaction based on exclusively intermittent renewable electricity likely requires some form of additional hydrogen buffer storage capacities or battery storage.
d) Lack of comprehensive regulation: The lack of regulation on the use of hydrogen as a shipping fuel, as well as handling and safety guidelines, is a challenge in commercialising the hydrogen pathway.
e) Efficiency: Current liquefaction plants are not optimised for efficiency and have high energy demands.
f) Safety: The risk of explosions through BOG and other potential leakages stems from the wide ignition limits of hydrogen/air mixtures and the low ignition energy of hydrogen.
g) Competitiveness: LH_2 transport and is highly dependent on the cost of energy and hydrogen.

Hydrogen metrology, being a key aspect of the H_2 value chain, is also affected by the challenges above, especially regarding the cryogenic temperatures (a), as will be discussed in Section 5. On the other hand, advancing hydrogen metrology TRL (b) can be a stepping stone to assist in overcoming other challenges, such as better inventory control as a palliative to intermittency (c). Further, demonstrated technologies will precede the enforcement of regulations (d), systems optimisation with the opportunity to decrease costs and enable competitiveness(e).

4.3.2 Challenges related to the physical properties of hydrogen

Table 2 shows the physical properties of hydrogen in contrast with other gases/liquids of interest.

Table 2. Physical properties of hydrogen (Source: IEA, 2019 [10])

Property	Hydrogen	Comparison
Density (gas)	0,089 kg/m3 (273K, 1bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m3 (20K, 1bar)	1/6 of LNG
Boiling point	20.4 K (1bar)	90 K below LNG
Mass Energy density (LHV)	120.1 MJ/kg	3x that of gasoline
Specific Energy (liquified, LHV)	8.5 MJ/L	1/3 of LNG
Ignition range	4-77% in air by volume	6x wider than methane

A relevant property of hydrogen is the ortho–para conversion of hydrogen. Orto-para conversion is the transition of nuclear atoms spinning in the same direction (orto) to spins in opposite directions (para). The reaction involves two hydrogen molecules. In the liquid phase in which the ortho–para conversion is spontaneous.

The orto–para conversion is critical for storage and transportation. Normal hydrogen, n-H_2, is the equilibrium composition occurring near the ambient conditions with a 75/25 % of o-H_2/p-H_2. If n-H_2 is liquefied without orto–para conversion, a portion of the liquid will boil and trigger mass vaporisation and energy losses. For long-term storage or transportation over long distances, it is essential to convert o-H_2 to p-H_2 [17]. A catalyst is used during liquefaction to speed up the transition. At cryogenic conditions, equilibrium requires 99.8% p-H_2 and 0.2% o-H_2 [18].

5 Hydrogen Metrology

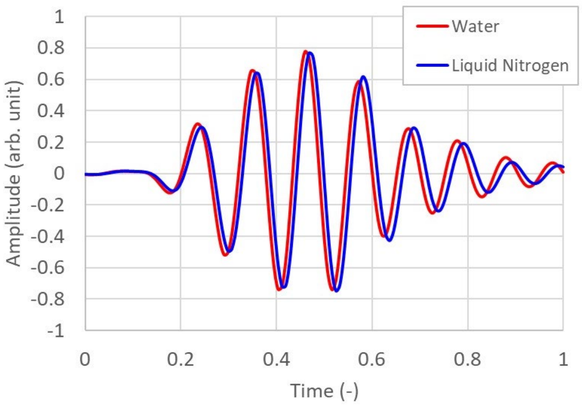
Sensors used today for liquid hydrogen service can be characterised as per application into (i) flow meters, (ii) level sensors, and (iii) mass measurement devices for static weighing. In the following the state of the art of the former two applications are discussed.

5.1 Flow meters

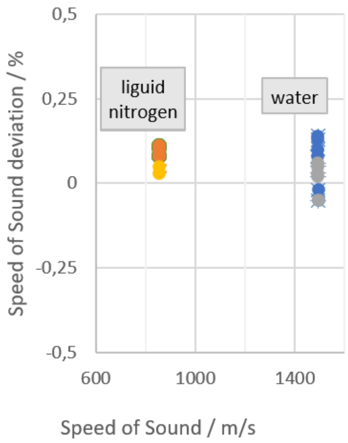
There are three main technologies with capabilities to measure flows of hydrogen, namely. Coriolis meters, Differential pressure devices, and Ultrasonic meters. One of the key challenges concerning liquid hydrogen flow measurement is related to the temperature of the fluid. Several theoretical methods and analyses have been performed based on calibrations at cryogenic temperatures with Liquid Nitrogen (LiN). For Coriolis meters, the transferability of water calibration to liquid hydrogen depends greatly on the calculation of the Young's modulus and Poisson's ratio of the tube material at LH_2 conditions.

Measurements from ultrasonic meters are fluid- and geometry-contingent. The thermal effect yielding from temperature differences of approximately 270 K between calibration and operation must be accounted for. To illustrate this, the thermal expansion on a pipeline cross-section is given by $\Delta D = \alpha D_i \Delta T$, where α is the material linear expansion coefficient, D_i is the initial inner diameter, and ΔT is the temperature difference. For stainless steel, a change in path length of over 0.50% is likely to occur.

Recently a cryogenic test setup for the characterisation of ultrasonic flowmeter in Liquid Nitrogen (LN_2) was developed in Germany. In [19] the authors report that the suitability of the transducers under cryogenic conditions was proven successfully showing a high signal quality (see Figure 5 (a)). The high accuracy of the speed of sound (see Figure 5 (b)) and the high stability of the transit time measurement under very different process conditions was demonstrated by comparing the results for LN_2 and water. This allows for ultrasonic flow meters to transfer measurement results under ambient conditions to an application under cryogenic conditions.



(a)



(b)

Figure 5. a) Signal comparison of an ultrasonic meter in water and liquid nitrogen (modified from [19]), b) speed of sound deviation for water at ambient conditions and for liquid nitrogen at -196°.

Other experiences for subcooled liquid services are worth revising to gain insight. LNG flow meters, for example, are usually calibrated using water at ambient temperatures and then corrected to cryogenic conditions using correction models specific to the flow metering unit. Yet for a thorough analysis to be performed, more information on calibrations of ultrasonic meters at cryogenic temperatures with, for example, Liquid Nitrogen or LNG is needed. To our knowledge, there is no independent, traceable study on the effect of cryogenic temperatures on Ultrasonic meters. In the only study of such characteristics conducted at VSL [20], automatic corrections were applied to all meters. In [21], some indication is given regarding the significant effect of improper insulation on Coriolis and ultrasonic meters. One of the ultrasonic technologies that took part in the tests campaign above reports up to 2.5% deviation in mass flow rate under un-insulated conditions [22]. Temperature compensation would also be required for LH_2 service. In [22], it is argued that for LNG, using water calibration and accounting for temperature uncertainty is only viable so long actual traceable data is available.

In short, experience and public information on the topic are very thin, and further research is required to ascertain the accuracy of metering technologies and the transferability of water to H_2 calibration.

5.2 Level meters

There are three level measurement principles of relevance for liquid hydrogen, namely pressure difference, radar, and floating gauges. The latter is based on capacitive measurements or, at a lower TRL, acoustic resonance, superconducting wire, or optical. Perhaps a less traditional capacitive device with prospective use in hydrogen both for level measurements as well as for flow measurement is Electrical Capacitance Tomography (ECT). ECT has been studied for imaging of sloshing, two-phase identification, density measurements, and tank-level measurements of cryogenic fluids [23-25]. The work in [24] is the first successful functionality tests with LH_2, within an accuracy level that is in line with expectations from space launch programs.

Off-the-shelf differential pressure level meters are available. For example, The VEGADIF 85 [26], is a universal differential pressure meter with a capacity to measure up to 2m levels and potential to be used for liquid hydrogen. However, its performance is uncertain for liquid hydrogen at temperatures of 20K. For processes at 233 K the manufacturer claims an accuracy of 0.065%. Performance for liquid hydrogen, the installation effects due to the need to connect tubing protruding the double insulated wall is unknown.

Opposite to differential pressure devices, radar tank gauges are integrated into the LH2 tanks. The GLA-310/5-LH2 radar is certified and has been used in the Suiso Frontier for the pilot project HESC [14]. The technology employs a Frequency-Modulated Continuous Wave (FMCW) principle. The RTG emits a frequency-sweeping microwave signal through a waveguide (standpipe). The distance is derived from the time delay of the reflected signal from the liquid surface. The radar is assembled in sections and adjusted to match the total tank height up to 50 m.

5.3 Facilities

Table 3 summarises existing experimental facilities of relevance for the advancement of hydrogen metrology. Besides the existing facilities, the authors have knowledge of two other experimental facilities in development. Such plans comprise (i) a New Speed of Sound cell designed for liquid hydrogen. Status: Funds granted – ThermoPropPy. Location: Ruhr University Bohum, Germany; (ii) Lab-scale apparatus for hydrogen liquefaction. Status: Proposal submitted – Funds pending. Location: SINTEF Energy Research, Norway.

Table 3 Overview of existing LH_2 test facilities

Facility location	P (bar)	T (K)	Flow rate	Fluid	Metering principle tested	Setup	Comments
ILK Dresden: Institut für Luft- und Kältetechnik gGmbH	N/A	N/A	Static	LN_2	Ultrasonic	Bench test	Reasonable signal response [19]
DRL: Deutsches Zentrum für Luft- und Raumfahrt	N/A	20	Static	LH_2 + GH_2	ETC	Probe in cryostat	Fill level measurement resolution < ±0.5mm compared to an alternative measurement system [24]
VSL - Rotterdam Europort - The Netherlands	6	93	$100 m^3/h$	LN_2	Coriolis + Ultrasonic	Traceable flow loop	Improper insulation of the flow meter can result in significant deviations from the reference mass flow rate [21]
DLR, Germany, Institute of Space Propulsion	>1bar	<21	up to 2700 kg/h	LH_2	Turbine and Coriolis	Labratory flow test	Turbine meter and Coriolis meter successfully tested

6 Conclusions

The EU and North America have in place decarbonisation strategies that consider hydrogen. Recent forecast studies agree that the transport sector will require around 55 Mt of hydrogen by 2050. Of this, the liquid hydrogen use is expected to be around 15 Mt. The demand for liquid hydrogen stems mainly from the need to transport hydrogen long distances from energy-rich sources to demanding economies, e.g., Australia to Japan. Another use for liquid hydrogen is the need to store large hydrogen quantities. Such storage needs encompass the refuelling of fuel-cell electric vehicles, barges, or ferries. Within the aviation industry, hybrid-hydrogen aircraft powered by liquid hydrogen will also require storage of hydrogen both on land and on the aircraft.

Most of the forecasting scenarios for a hydrogen economy are very optimistic and rely on ambitious hypotheses such as fast readiness, deployment, and acceptability of hydrogen. Yet, current trends of the hydrogen market, lean towards a 'Business as Usual Scenario'.

The realisation of a hydrogen economy has various challenges that need to be overcome in the immediate future. Advancing hydrogen metrology, TRL can help overcome some of such challenges, e.g., by providing better inventory control as a palliative to intermittency. High TRL measurement technologies can also assist in building a common understanding of the performance of the processes necessary to enforce regulations and for process optimisation, yielding decreased costs.

State-of the art of metrology for liquid hydrogen, encompassing flow meters and level sensors, was discussed. There is, however, very limited publicly available bibliography. One of the main key challenges concerning liquid hydrogen flow measurement is related to the temperature of the fluid. Previous tests with liquid nitrogen (at 93 K) showed that improper insulation of the flow meter can result in significant deviations from the reference mass flow rate. Thus, performance studies of Coriolis and Ultrasonic meters, and possibly calibration under similar operating conditions, are required. There are few studies on the performance of level meters for liquid hydrogen. Off-the-shelf differential pressure level meters are available yet the accuracy for liquid hydrogen is uncertain. Initial functionality tests of electrical capacitance-based systems used for imaging tank-level measurements of cryogenic fluids show positive results. Radar tank gauges integrated into the LH_2 tanks are perhaps the most advanced technology. Such a method was used in the pilot project HESC. The advancement of metrology for hydrogen requires experimental facilities and controlled conditions. A summary of existing and upcoming facilities of interest has been summarised.

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