Hy2Market

D3.5: High level study on the size, cost-base, benefits, regional/ international applications and suitability of liquid hydrogen for the Northern Netherlands

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Acknowledgements

This paper has been developed to assess the suitable size, cost-base, benefits, and regional/international applications for Liquid Hydrogen (LH_2), with a focus on LH_2 transport use cases in the Northern Netherlands as a means of decarbonising this sector.

This deliverable has been prepared within the Hy2Market project, which has received funding under Grant Agreement No. 101083592 from the Interregional Innovation Investments (I3) Instrument, under the European Regional and Development Fund (ERDF), managed by the European Innovation Council and SMEs Executive Agency (EISMEA).

The authors would like to acknowledge that earlier exploratory work on liquid hydrogen in the Northern Netherlands was undertaken within the HEAVENN project funded by the Fuel Cells and Hydrogen 2 Joint Undertaking, now Clean Hydrogen Partnership, under Grant Agreement No. 875090, and the Province of Groningen. That work enabled investigation of the potential of locating a LH_2 plant in Eemshaven/Delfzijl, taking energy from proximal North Sea renewables and supplying regional hydrogen applications, with a focus on road transport.

The present Hy2Market deliverable expands on this prior work by considering LH_2 as a regional energy import mechanism from lower cost, hydrogen rich areas. It has contributed additional information to and enhanced elements of all chapters beyond and including Chapter 6. With this valuable addition in this high-level study, that was made possible with the Hy2Markt i3-funding, we can show how applications of (liquid) hydrogen in the regional value chain benefit the region and what is required to make the portside technology ready for importing and production of LH_2.

Executive Summary

It is now well understood by both industry and policymakers in Europe that green hydrogen, produced by electrolysis, can displace fossil fuel use in challenging to electrify sectors such as industry, chemicals, and heavy transport. Hydrogen targets set by the EU for 10 million tonnes of domestic production by 2030[1] in addition to mandates for e-fuels in shipping and aviation, mean that the green hydrogen industry is set for unprecedented growth this decade. Uncertainty persists however, around how exactly such targets will be achieved, particularly pertaining to where this hydrogen will be produced and used, and how it will be stored and transported, both within Europe, and globally.

LH_2 has a higher density than GH_2. This is advantageous for both storage and transport of H2. The Netherlands has significant LH_2 experience, with a liquefaction plant located in Rotterdam. There are plans to renew and upgrade this facility adding a further plant, which would mean that 50% of Europe's hydrogen liquefaction capacity will be in the Netherlands. This study examines the potential for a liquefaction facility in the northern Netherlands and compares it to the pros and cons of an import terminal, with a particular focus on Delfzijl, with its significant industrial base, and proximity to the Port of Eemshaven.

A number of existing industrial uses of hydrogen at the chemical cluster in Delfzijl, as well as potential future end-users of hydrogen including Groningen Airport, Eelde, the first hydrogen valley airport in Europe, have been identified. LH_2 may be used as an aviation fuel for short-medium distance flights. If a regional airport similar in size to Groningen were to convert 10% of the aviation fuel consumption to LH_2, this would require 5,000 tonnes per year, or 14 tonnes per day[2]. This demand for hydrogen is unlikely to materialise until the late 2030s, as LH_2 aircraft are still a nascent technology in a heavily regulated industry with stringent safety and certification standards. Other significant potential end-users of LH_2 in the region include the maritime/inland shipping industries, and heavy-duty vehicle refuelling.

With a vast resource of offshore wind nearby, and decades of experience in hydrogen and chemicals, the Northern Netherlands can position itself at the forefront of the green hydrogen industry. There are many hydrogen end-uses which can make use of its liquid form's higher

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[1] REPowerEU. The European Commission. Accessed at: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52022DC0230 (2022)

[2] Hydrogen Powered Aviation. Fuel Cells and Hydrogen Joint Undertaking. Accessed at: https://www.clean-aviation.eu/media/publications/hydrogen-powered-aviation (2020)

energy density, compressibility and purity. Accessing such a high-value clean product in the Northern Netherlands has the potential to accelerate emissions reductions in industry, chemicals, and energy, and increase energy security and dependence. By building on its already large share of the LH_2 market in Europe, the Netherlands could also supply identified end uses in neighbouring countries. Suitable cryogenic tankers have been used to move large volumes across long distances in the US and Europe for decades, and, if investments are synchronised with demand growth, the northern Netherlands could position itself as a primary clean LH_2 region in northwestern Europe.

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1 Introduction

Hydrogen is an energy vector that has the potential to enable widespread carbon emission savings in hard-to-abate sectors. Additionally, hydrogen is an excellent medium for large-scale energy storage, and can alleviate pressure on constrained grids to enable greater penetration of renewables without the need for expansion of electrical infrastructure.

In 2022, hydrogen made up less than 2% of Europe's energy consumption, with global hydrogen demand at 95 million tonnes in the same year[3] mainly used to produce products such as fertilisers, plastics, and de-sulfurized oils. In Europe, >95% of hydrogen is produced using natural gas, resulting in significant carbon emissions. To support transition of existing hydrogen use, and enable further decarbonisation via clean hydrogen, the EU has announced a number of initiatives to support the sector's development. This includes targeting 10 million tonnes of green hydrogen production via 40GW of electrolysis capacity by 2030 in the EU hydrogen Strategy, supported by imports of a further 10 million tonnes in the same time frame[4] within RePowerEU legislation. The Netherlands, in support of this effort, adopted a national hydrogen strategy targeting 4 GW of installed electrolyser capacity by 2030, 10% of the EU's goal. Key to the national plan is the North of the country, which aims to produce 65 PJ of clean hydrogen per year, leveraging its offshore wind potential and strong industrial base. Over the last few years, the local hydrogen sector continues to explore ways to expand its production capacity not only to meet existing industrial demands but also support new areas such as mobility.

The Netherlands' energy system remains heavily reliant on fossil fuels, with oil and gas making up 84% of energy consumption in 2020. Major emitters, energy, transport, and manufacturing, collectively released over 115 million tonnes of CO_2, more than half of national emissions. In response, the Dutch government has made large-scale renewable energy deployment a priority, especially offshore wind. The North Sea, with its shallow waters and proximity to industrial ports, offers an ideal environment for this. Recognising this, the Netherlands increased offshore wind targets in 2024 to 21 GW by 2030 and 50–70 GW by 2040–2050. However, intermittent renewable generation and limited grid flexibility pose storage challenges. Hydrogen offers a practical solution, especially in storing surplus wind energy and ensuring consistent supply.

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3 Hydrogen. International Energy Agency. Accessed at: https://www.iea.org/energy-system/low-emission-fuels/hydrogen (2023)
4 Hydrogen. The European Commission. Accessed at: https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en (2023)

The Northern Netherlands, historically a major natural gas producer of European-scale due to the Groningen field, has existing infrastructure and expertise that can be repurposed for hydrogen. Groningen, in particular, is home to Europe's first hydrogen valley, HEAVENN, a €96 million EU-supported initiative to develop a regional hydrogen ecosystem integrating production, infrastructure, mobility, and built environment use cases. The project has significant plans to initialise electrolysis capacities via onshore and offshore renewables farms, positioning the region to become one of the Netherland's leading green hydrogen hub.

However, gaseous hydrogen will not always meet operational requirements in some sectors as its energy density cannot provide the necessary amount of storage (and in turn, sustained power) for certain needs and applications. Liquid hydrogen can overcome these obstacles, as well as providing a higher hydrogen purity. This report examines the properties, production process, storage, distribution, and applications of LH_2. These insights will be applied to a regional case study to evaluate establish the case for LH_2 in the Northern Netherlands and how it can significantly contribute to decarbonisation while maintaining a commercial business model.

Currently the LH_2 market is limited to niche applications with a global demand of around 135 thousand tonnes in 2023[5], less than 0.15% of total global hydrogen demand. However, the market is expected to grow significantly in coming years, roughly doubling in size within the next decade. The main drivers for this increased demand come from the critical sectors of mobility, aerospace, large scale distribution (import, export, and long-distance road-bases distribution) and cooling for multiple applications. These sectors, including heavier methods of transport, such as aviation, maritime and heavy-goods-vehicles, are anticipated to reap benefits from a number of LH_2's properties, especially its considerable higher energy density in comparison to compressed gaseous hydrogen.

When deciding on which energy carrier to use, impact across the full value chain should be considered. Each has different benefits and costs. Adoption and use challenges also vary. This report will provide base information to enable LH_2 to be assessed within the Northern Netherlands' developing hydrogen infrastructure.

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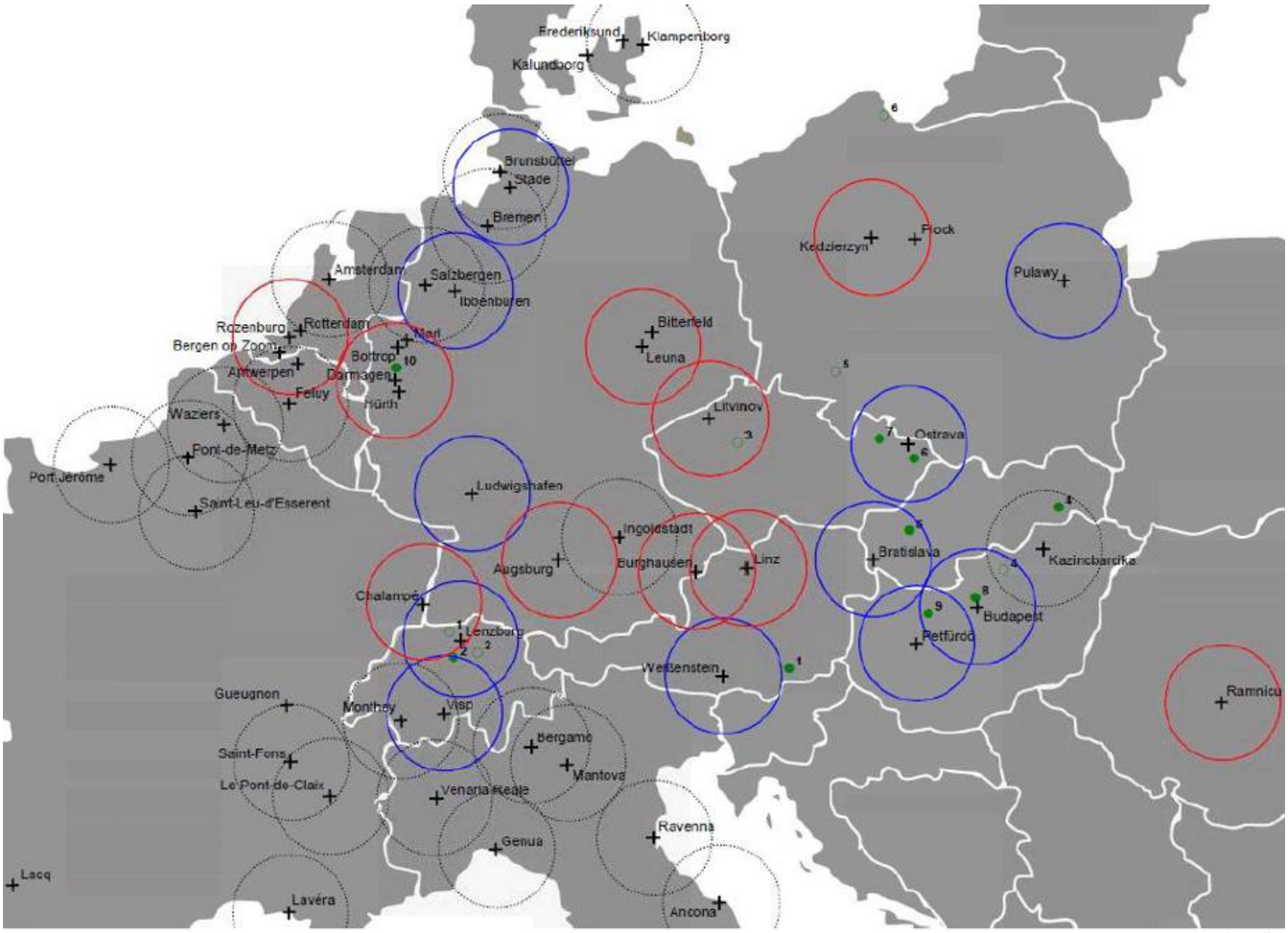
[5] LIQUID HYDROGEN MARKET SIZE & SHARE ANALYSIS - GROWTH TRENDS & FORECASTS (2023 - 2028). Mordor Intelligence. Accessed at: https://www.mordorintelligence.com/industry-reports/liquid-hydrogen-market (2022)

2 Liquid Hydrogen Market History

LH_2 has been used since the 1950s in multiple applications, with only a number of select stakeholders capable of supplying liquefaction equipment on a commercial scale. It is the main trucked hydrogen delivery method in the US due to historic strategic focuses and the long distribution distances between sources and customers making its increased energy density preferred. It is not currently used in any other geography as the dominant hydrogen delivery method with LH_2 value chains existing, instead, around specific liquid-preferred applications. However, new energy applications are in their development phases which have the potential to increase the prevalence of LH_2 over other decarbonised energy vectors, including gaseous hydrogen.

In the US, historic development and demand has been driven by the needs of the original NASA space programmes. Once installed the LH_2 production plants needed to be used on a more continuous basis to achieve commerciality, hence the IGCs, especially Air Products, drove the trucked market towards LH_2. In this environment, compressed hydrogen is restricted to a more regional position. IGCs operate a hub and spoke model due to high capital costs. This leads to compressed hydrogen molecule pricing tending to be higher than in its liquid state, therefore, as payloads are also lower, it is a very local sourcing method. As a result, many US by-product hydrogen sources have been ignored by the IGCs due to their focus on LH_2.

In Europe, the IGCs have tried to introduce LH_2 into a gaseous dominated market. Each IGC made an investment decision for its own LH_2 plant in the 1970s/80s. These are now running but the market has not developed along the same lines as it did in the US. The Ariane engine test programme and the electronics industry provided a sink for some molecules, however, the density of hydrogen sourcing vs each source's proximity to its customer base ensured that LH_2 did not penetrate the industrial market - except for customers with specific requirements.



Source: Messer internal study

Figure 1. Continental Europe Gaseous Hydrogen Sources c.2018 (with a 100km distribution radius)

European gaseous hydrogen molecules are available at a lower delivered cost than LH_2. Essentially this is due to the number of exploited by-product sources and reasonable distribution distances, so the merchant hydrogen business remains dominated by tube trailers.

The main historic barriers to entry in a new market for LH_2 are the capital costs associated with the liquefaction and production plant, storage system and distribution/customer equipment. Liquefaction of hydrogen is costly in energy terms, although, once in place, it can provide significant advantages in terms of volumes of hydrogen transported per load. These aspects will be examined in the subsequent sections.

3 Properties of Liquid Hydrogen

LH_2 has a volumetric density close to 71kg/m³ at 1.013 bar, roughly 14 times less dense than water. In comparison, gaseous hydrogen has a volumetric density of 26.1kg/m³ at 350 bar and 42kg/m³ at 700 bar [6], making it significantly less volumetrically dense than its liquid analogue. This higher volumetric density means LH_2 can store a larger amount of energy in a given storage tank, making it more suited for energy intensive applications (>2,300 kWh/m³ in comparison to 870 – 1,400 kWh/m³ when assuming hydrogen's gravimetric energy density of 33.33 kWh/m³)[7].

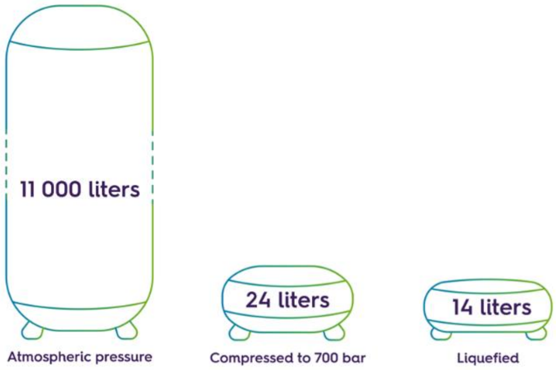


Figure 2. Storage volume for 1kg of hydrogen in different state[7]

Hydrogen is gaseous in its natural state. The process of liquefication requires hydrogen to be cooled to below -252.9°C and then stored and distributed within cryogenic tanks. These tanks are vacuum insulated to prevent heat reaching the LH_2 and causing it to boil off, where hydrogen transitions back to its gaseous state due to heat ingress into the vessel. These storage tanks come in various shapes and sizes and differ markedly from gaseous hydrogen storage which are mainly capsule shaped and designed to contain higher pressures. Instead, cryogenic tanks for LH_2 are usually cylindrical or, at larger scales, spherical[8].

Figure 3. AP's Cylindrical Storage[8]

Such tank designs have been developed to minimise surface area-to-volume ratio which reduces boil off. Boil off is reported as percentage of stored hydrogen lost per day due to evaporation, which in cryogenic spherical tanks is usually below 0.1%[9]. These tanks are typically made from stainless steel or aluminium, but

[6] The energy density of hydrogen: a unique property. DEMACO. Accessed at https://demaco-cryogenics.com/blog/energy-density-of-hydrogen/ (2023)
[7] Hydrogen storage: a challenge for the development of the industry. Terega. Accessed at: https://www.terega.fr/en/our-activities/hydrogen/hydrogen-storage-a-challenge-for-the-development-of-the-industry/ (2025)
[8] Air Products Liquid Hydrogen Tank. http://www.ctmeurope.co.uk/#jp-carousel-2896
[9] Hydrogen Storage Methods. SynerHy. Accessed at: https://synerhy.com/en/2022/02/hydrogen-storage-methods/ (2022)

some entities, such as the National Composites Centre in the UK, have begun testing composite cryogenic tanks[10] - which are especially interesting for onboard vehicle storage solutions. Traditional tanks are double walled with a gap between them minimising heat transfer through convection or condensation via creation of a vacuum layer.

Smaller-scale storage tanks have greater insulation to counter-act increased boil off rates due to lower surface area-to-volume ratios, but still exhibit higher levels of boil off despite this[11]. Figure 4a and 4b showcases how the size and shapes of LH_2 storage tank affect the rate of boil off.

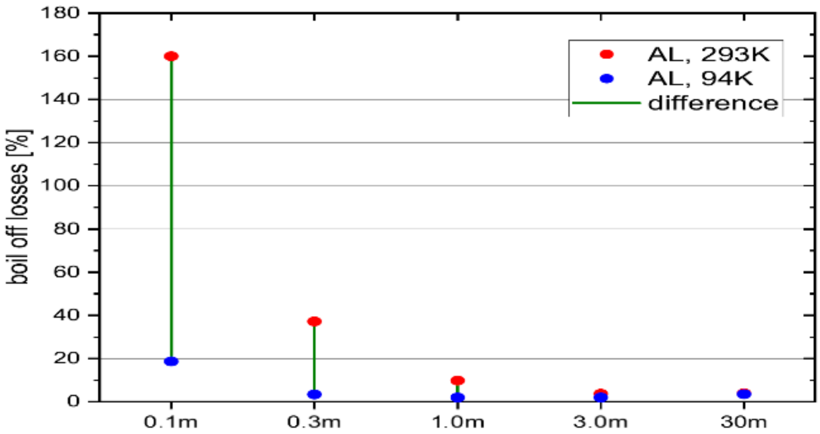


Figure 4a. Boil off rates by storage size[11]

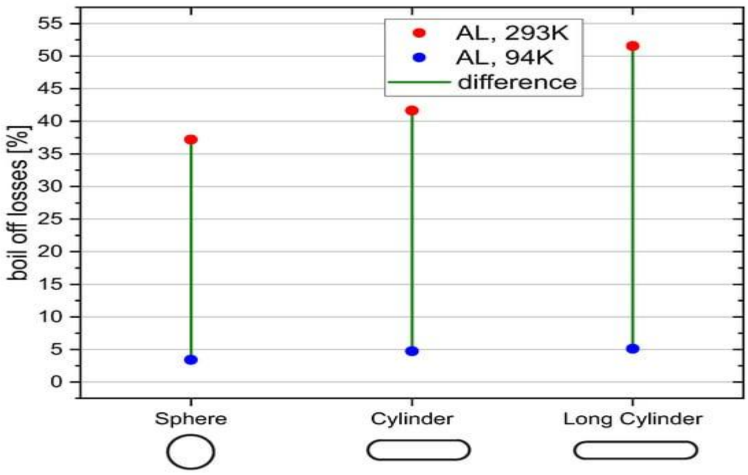


Figure 4b. Boil off rates by storage shape[11]

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[10] National Composites Centre. Composite cryogenic tanks tested with liquid hydrogen by National Composites Centre. Accessed at: https://www.nccuk.com/news/composite-cryogenic-tanks-tested-with-liquid-hydrogen-by-national-composites-centre/ (2023)

[11] Reducing Hydrogen Boil-Off Losses during Fuelling by Pre-Cooling Cryogenic Tank. Ghaffari-Tabrizi, F, et al. Accessed at: https://www.mdpi.com/2673-4141/3/2/15#:~:text=Relative%20boil%2Doff%20losses%20are,be%20evaporated%20for%20larger%20tanks. (2022)

4 Hydrogen Liquefaction Process

Hydrogen liquefaction is the process of turning gaseous hydrogen, typically produced at scale by an electrolyser or steam methane reformer (SMR), into its liquid form. This occurs when hydrogen is cooled down to its boiling point of -252.9°C. The process is very energy intensive and requires between 10-20kWh per kilogram of LH_2 equivalent to c. 30% of its energy content.To understand what happens within hydrogen liquefaction process, first we have to look at the atomic level of hydrogen.

Hydrogen is a molecule that exists in our atmosphere in pairs of atoms - H_2 or dihydrogen. In this form hydrogen has two isomeric forms, ortho and parahydrogen. The difference between ortho and parahydrogen is the rotation of the hydrogen nuclei. In orthohydrogen the spins of the two hydrogen nuclei are the same, whereas in parahydrogen, they are antiparallel (opposite), which results in the molecule having less energy and a difference between their magnetic states[12]. Parahydrogen, as the most stable and lowest energy form of hydrogen, is more present at lower temperatures and will make up >99% of molecules at boiling point compared to just 25% at room temperature.

Therefore, during the liquefaction process, due to the temperature decrease, ortho-hydrogen transitions to para hydrogen. This change is exothermic, resulting in a release of heat. This must be managed/designed for during liquefaction to prevent excessive energy use.
This section considers the technology and stages that occur within such a liquefaction process/plant.

[12] Parahydrogen. University of York. Accessed at: https://www.york.ac.uk/chym/parahydrogen/#:~:text=The%20difference%20between%20para%20and,between%20the%20two%20magnetic%20states.

4.1 Generic process

The typical hydrogen liquefaction process has four main stages; Pre-compression (dependent on Feed pressure), Pre-cooling, Cryogenic cooling and Expansion before we have a LH_2 product.

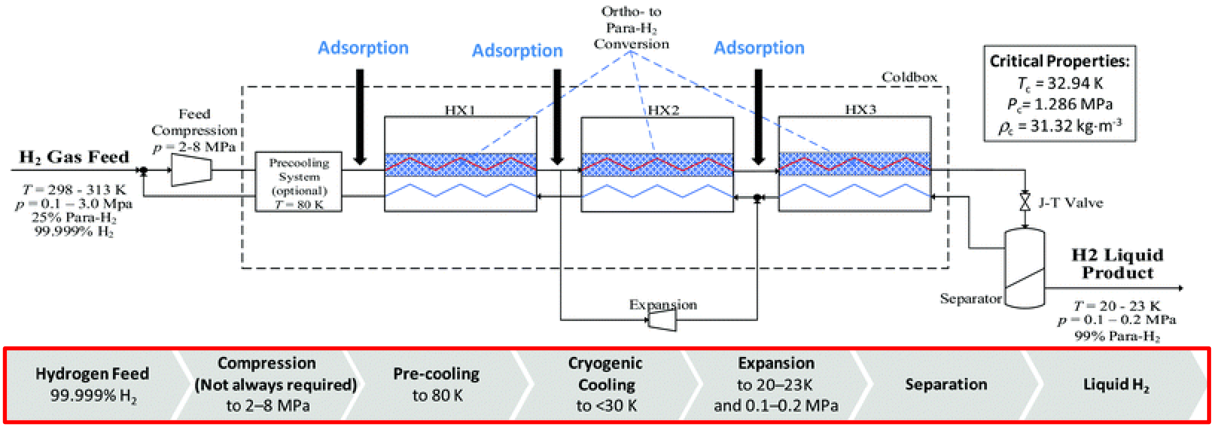

Figure 5. Hydrogen Liquefaction process based on the Claude cycle[13]

4.1.1 Feed hydrogen

Firstly, hydrogen must be fed into the cooling system at low pressures, typically between atmospheric and 30 bar (3Mpa).

4.1.2 Pre-compression

This stage is dependent on the pressure of gaseous hydrogen fed into the hydrogen liquefier. If the hydrogen feed has a low pressure, then it will require this step before it can be cooled. In most hydrogen liquefaction facilities, the pressure of the feed hydrogen gas required is 20 bar, the output from most SMR process is lower than this (c. 3-25bar) and therefore requires pre-compression. Electrolysis systems are migrating to producing hydrogen at higher pressures, i.e. c. 30 bar, negating the need for feed compression.

4.1.3 Pre-cooling

An initial pre-cooling and adsorption phase is undertaken to ensure the hydrogen feed is sufficiently pure. Given the cryogenic temperatures reached in the liquefaction process, most impurities, including water vapour, oxygen, nitrogen, argon, trace elements from any electrolyte (from electrolysis) or from the distribution method used to move the gaseous hydrogen into the liquefaction facility, will solidify. Such solid material presents safety and process risks to the equipment as it can clog and reduce flows creating issues within the compressors or cold boxes. This precooling usually occurs at -191°C and represents between 20-25% of the total energy used in hydrogen liquefaction.

4.1.4 Cryogenic cooling

The hydrogen is then further cooled to below -243°C using a closed-loop cryogenic refrigeration cycle, which involves either continuous or batch catalytic conversion of ortho to parahydrogen. This stage, due to the extreme temperatures required, is also the most energy intensive stage in the process, using between 50-65% of total exergy used throughout.

4.1.5 Expansion

This last process step is known as adiabatic expansion, where the hydrogen is cooled to its boiling point -252.9°C and stored at 1 to 2 times atmospheric pressure. This expansion occurs primarily in two ways. Either via making use of the Joule-Thompson effect for hydrogen (i.e. temperature change due to pressure change) which will result in cooling the gas stream across a flow restricting valve or by using an expansion turbine[13].

4.1.6 Operation

Liquefaction facilities are less flexible in ramping up or down compared to other components of the hydrogen value chain. Typically, these systems can reduce their output by up to 50%. However, long-term interruptions in supply of hydrogen can jeopardise plant integrity, unless coordinated with maintenance activities. Should the facility be shut down temporarily, the cold box temperatures would normally be maintained as it is very time-consuming to cool down once warm. However, preserving such cryogenic temperatures is also highly energy-intensive, so an economic assessment is made. Ramping down beyond 50% or turning off the cold box entirely will also lead to more frequent maintenance and service intervals, which can be expensive due to the complexity of the system itself.

5 Liquid Hydrogen Regulation, Codes and Standards

As with gaseous hydrogen, the handling, storage, and use of LH_2 is governed by a rigorous framework of codes, standards, and regulations designed to ensure safety for operators, users, and surrounding communities. This framework is shaped by a range of institutions, from international standard-setting bodies to regional authorities and industry-specific organizations.

At the global level, the International Organization for Standardization (ISO) establishes foundational safety and design standards that are widely adopted across the hydrogen sector. In

[13] Hydrogen liquefaction: a review of the fundamental physics, engineering practice and future opportunities. Royal Society of Chemistry. Accessed at: https://pubs.rsc.org/en/content/articlehtml/2022/ee/d2ee00099g (2022)

Europe, these are complemented by the European Norms (EN), which provide regionally tailored guidance to ensure consistency within EU member states. Additionally, industry-led entities such as the American Petroleum Institute (API) play a key role by issuing detailed technical standards for specific equipment and infrastructure, many of which are applied internationally across hydrogen and energy industries.

These standards play a vital role in supporting the safe and scalable deployment of LH_2 across energy and industrial sectors. As demand grows and applications diversify, particularly in mobility, shipping, and aviation, the regulatory framework is expected to evolve in parallel. This evolution will not only reinforce safety requirements but also encourage the harmonisation of components and systems. Standardisation enables greater interoperability between suppliers, reduces engineering complexity, and lowers project costs by allowing the use of competitively sourced equipment without compromising compliance.

Area	Standard / Regulation	Body	Scope / Relevance
Liquefaction	ISO 21010	ISO / CEN	Compatibility of gases and materials for cryogenic systems (important for LH_2
Liquefaction	EN 60079 (ATEX)	CEN / EU Directive	Equipment for explosive atmospheres - applies to liquefaction facility zones
Liquefaction	PED 2014/68/EU	EU	Pressure Equipment Directive - applies to LH_2 liquefaction vessels and systems
Liquefaction	ISO 13985	ISO	LH_2 - Fueling system interface - includes thermodynamic and fluid control specifications
Storage	EN 13458-1/-2	CEN (EU)	Cryogenic vessels - Static vacuum insulated storage for LH_2
Storage	ISO 21009-1	ISO / CEN	Design and operation of transportable cryogenic storage (ISO-aligned)
Storage	ASME BPVC Section VIII	ASME / Netherlands	Widely referenced for LH_2 tank design in absence of EU-specific standards
Distribution	ADR 2023	UNECE / EU	Road transport rules for dangerous goods, including liquid hydrogen tanks
Distribution	EN 12807	CEN (EU)	Cryogenic couplings - relevant for LH_2 unloading/loading between ships, tanks
Safety / Permitting	ATEX 2014/34/EU + 99/92/EC	EU	Mandatory for all electrical/mechanical LH_2 zones - explosion prevention
Safety / Permitting	ISO/TR 15916	ISO / CEN	Basic safety considerations for hydrogen technologies - includes cryogenics
Safety / Permitting	PGS 35 (in development)	Netherlands (PGS)	Will govern Dutch LH_2 refueling and storage installations - public safety guidelines
Safety / Permitting	Omgevingswet (2024)	Dutch Government	Environment Act framework under which LH_2 infrastructure is permitted and licensed

Figure 6. Selected Standards, Codes and Regulations for the LH_2 value chain

6 Liquid Hydrogen Today

6.1 Global Technology Platforms

Due to the scale of investment requirements for LH_2, technology development by organisations is globally aligned. Historically, technology has come from a small number of companies. These technology leaders tend to have centres of excellence which support regional infrastructure roll out. The increased interest in LH_2 for new applications such as aviation and increased security of supply is catalysing development and so proliferating supply chain options.

Costs have continued to go down in recent years, as the largest LH_2 production facility in America is located in Nevada, owned by Air Liquide cost a $250 million investment and has the ability to produce around 30 tonnes of LH_2 a day ($8.3m/tpd), providing enough renewable hydrogen to power of 40,000 fuel cell electric vehicles[14]. This cost of the entire facility development, including site acquisition, construction and engineering design, as well as an SMR to produce the hydrogen needed for liquefaction.

6.2 Production

In today's market, LH_2 is produced mainly in North America, Europe and Asia, with capacities ranging from small demonstrations and test facilities of less than 1 tonne per day to plants delivering larger quantities of 80 tonnes per day.

6.2.1 US

The US leads globally in LH_2 capacity, with its long history dating back to the 1950s. That legacy infrastructure has supported broader adoption, especially as the US lacks a nationwide hydrogen pipeline network. Instead, LH_2 has become the primary method for large-scale hydrogen distribution and storage across such a vast territory. Facilities are currently operating in California, Nevada, Texas, Georgia, and Tennessee, with further projects in development, including Plug Power's 45 tpd green hydrogen plant in New York. The US currently has ten times the liquefaction capacity of the EU, and expansion plans aim to increase this to well over 300 tpd in the near future.

The US, as of May 2024, has 145tpd of liquefaction capacity under construction across four plants, including a 75tpd facility in Alabama, NY. At the same point in time, 345tpd of liquefaction

[14] Air Liquide inaugurates in the U.S. its largest liquid hydrogen production facility in the world. Air Liquide. Accessed at: https://usa.airliquide.com/air-liquide-inaugurates-us-its-largest-liquid-hydrogen-production-facility-world (2022)

capacity was in planning across 9 projects, with one project aiming to develop a 90tpd facility in LaSalle, IL[15].

6.2.2 Europe

There are several key global LH_2 operators including Linde, Air Products, Air Liquide and Plug Power. Figure 7 outlines the capacities, commissioning dates and locations for liquefaction in Europe.

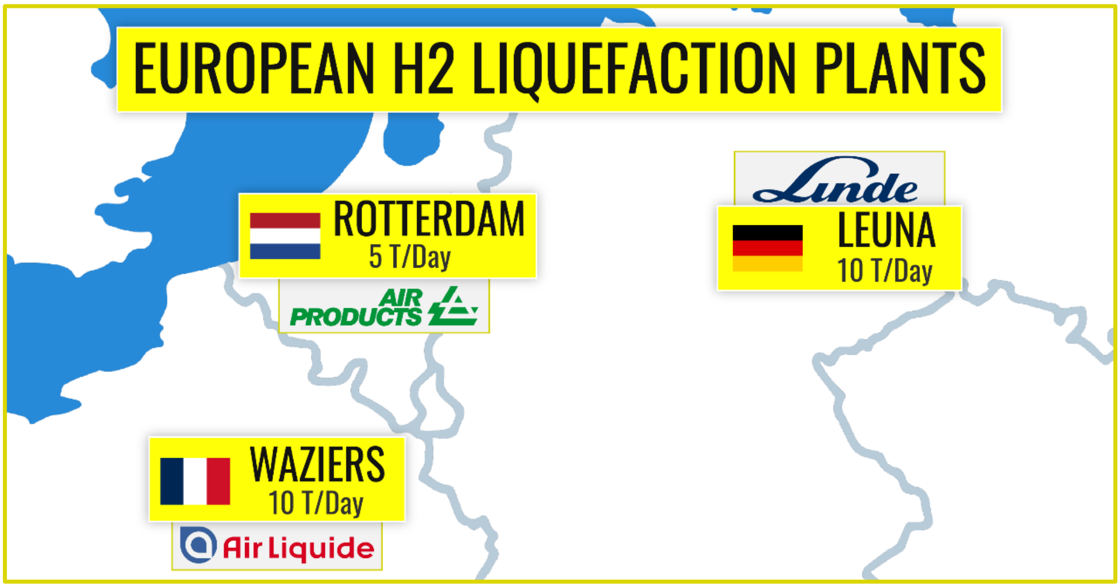

Figure 7. European H_2 Liquefaction Plants

The development of new LH_2 infrastructure is accelerating globally, with several major projects planned or underway. In Europe, the continent's liquefaction capacity is set to expand significantly. Gen2Energy are developing a 30 tonnes per day (tpd) project in Norway for the region's maritime applications and hydrogen transfer to the Netherlands. The LH_2 will be distributed to Amsterdam, where it will be converted back to gaseous form and utilised by Tata Steel for green steel production[16]. Air Products is planning a similar sized liquefaction plant, with hydrogen disassociated from imported ammonia arriving at Rotterdam's LNG terminal. The ammonia will originate from the 2.2 GW NEOM green hydrogen project in Saudi Arabia, and once converted to LH_2, it will be distributed to industrial end users across Germany. These facilities alone will treble Europe's current liquefaction capacity, marking a significant step toward strengthening the region's hydrogen supply chain.

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[15] Hydrogen Liquefaction Capacity in the United States. Department of Energy. Accessed at: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/24003-hydrogen-liquefaction-capacity-united-states.pdf?sfvrsn=b894666d_1 (2024)

[16] Tata Steel and ECOLOG are collaborating on a liquid hydrogen and CO2 corridor between Norway and Amsterdam. Tata Steel. Accessed at: https://www.tatasteelnederland.com/nieuws/en/tata-steel-and-ecolog-are-collaborating-on-a-liquid-hydrogen-and-co2-corridor-between-norway-and-amsterdam (2024)

6.2.3 Asia & Oceania

Turning to Asia and Oceania, several countries are rapidly advancing their LH_2 capabilities. South Korea is positioning itself as a regional leader, with Air Liquide developing a 90 tpd liquefaction facility, one of the largest planned worldwide. In Japan and South Korea, LH_2 is seen as a key enabler of hydrogen mobility and high-volume energy storage. Meanwhile, China has been producing LH_2 for decades, driven by the same challenges faced in the US, the high cost and inefficiency of distributing gaseous hydrogen over long distances.

In Oceania, Australia is aiming to become a major exporter of LH_2, primarily to markets in Japan and South Korea. Large-scale projects are under development to convert renewable hydrogen into a form suitable for long-distance export, further reinforcing the role of LH_2 in the emerging global hydrogen trade.

Country	Location	Operator	Capacity (metric tpd)	Commission date
USA	Ontario, CA	Linde	27.2	1962
USA	New Orleans, LA	Air Products	31.8	1977
USA	New Orleans, LA	Air Products	31.8	1978
USA	Niagara Falls, NY	Linde	18.2	1981
USA	Niagara Falls, NY	Linde	18.2	
Canada	Sarnia Ontario	Air Products	29	1981
USA	Sacramento, CA	Air Products	5	1986
Canada	Monterial	Air Liquide	10	1986
Canada	Bacancour Quebec	Air Liquide	11	1988
Canada	Magog, Quebec	Messer	15	1989
Canada	Monterial	Linde	14	1990
USA	McIntosh, AL	Linde	27	1995
USA	East Chicago, IN	Linde	27	1997
USA	Calvert City, KY	Air Liquide	9.1	2016
USA	La Porte, TX	Air Products	27	2021
USA	La Porte, TX	Linde	27	2021
USA	North Las Vegas, NV	Air Liquide	30	2022
USA	Woodbine, GA	Plug Power	15	2024
USA	Charleston, TN	Plug Power	9.1	2024
USA	St Gabriel, LA	Plug Power	15	2025
Netherlands	Rotterdam	Air Products	5	1987
France	Waziers	Air Liquide	10.5	1987
Germany	Leuna	Linde	5	2008
Germany	Leuna	Linde	5	2021
Japan	Osaka	Iwatani	11.3	2008
Japan	Tokyo	Iwatani	10	2008
Japan	Ichihara	Iwatani	5.1	2009
Japan	Shunan	Yamaguchi	5.1	2013
South Korea	Ulsan	Hyosung & Linde	35	2023
South Korea	Changwon	Doosan Energy	5	2024
South Korea	Wonchang-dong	SK E&S	82	2024
Kazakhstan Russia	Baikonur Plesetsk	Cryogenmash	4-17	~1960

Figure 8. Existing and Operational Liquid Hydrogen Production Plants (>5tpd)

6.2.4 Targets and Future Development of Liquefaction

In 2019, the US Department of Energy reported that the total cost of a hydrogen liquefaction plant facility at the time ranged between $50 million to $800 million for capacities produces between 6-200tpd respectively[17] ($4-8.33m per hydrogen tonne/day). However, the upper end of these costs were estimates, as such facilities are currently only theoretical. Scaling up of liquefaction technology has begun with plants greater than 75tpd coming online, such as the 80tpd site in South Korea, which was commissioned in 2024. Other sites are earmarked and in development such as 90tpd plants in USA.

A JRC report by the EU in 2022 stated a capital investment for a LH_2 plant is $2.5-5 million per hydrogen tpd[18]. The cost of the extremely energy intensive liquefaction process itself requires between 11.9-15 kWh per kg of energy to achieve[13], which when using the EU 2024 average electricity price[19], makes the energy cost of liquefaction range between €2-2.85 per kg at €0.1899kWh. However, with more renewable energy deployment in the coming years, these costs will come down especially with an increase in liquefaction efficiency. An IEA report in 2022 states the US DoE has set a target for capital costs of large-scale hydrogen liquefaction plants of 300 tonne per day (tpd) to cost $142 million excluding storage[20] ($0.473m/tonne/day).

Some companies, universities and other interested parties are researching how to increase the efficiency of this hydrogen liquefaction process and bring it closer to the theoretical energy levels required. With governments and regulatory bodies understanding the importance of LH_2's future in the EU's NetZero targets, projects are being funding to help improve the efficiency of this process. This is exemplified by HyLICAL, a European funded project coordinated by the Institute for Energiteknikk, Norway, which is seeking to reduce the energy intensity of hydrogen liquefaction to 8 kWh/kg by using the innovative magnetocaloric effect. This process could increase energy efficiency by >20% for LH_2 projects <5 tonnes a day and up to 50% for projects >5 tonnes a day, whilst decreasing capital expenditure by at least 20%, thereby having huge impacts on the sector if the project achieves its objectives[21]. Another method to bring down

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[17] DOE Hydrogen and Fuel Cells Program Record 19001: Current Status of Hydrogen Liquification Costs. Department of Energy. Accessed at: https://www.hydrogen.energy.gov/pdfs/19001_hydrogen_liquefaction_costs.pdf (2019)

[18] JRC Publications Repository. Assessment of hydrogen delivery options. Accessed at: https://publications.jrc.ec.europa.eu/repository/handle/JRC130442 (2022)

[19] Electricity price statistics. Eurostat. Accessed at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#Electricity_prices_for_non-household_consumers (2025)

[20] Global Hydrogen Review 2022. International Energy Agency. Accessed at: https://iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobaLH2drogenReview2022.pdf (2022)

[21] Development and validation of a new magnetocaloric high-performance hydrogen liquefier prototype. European Commission. Available at: https://cordis.europa.eu/project/id/101101461 (2023)

energy costs and improve energy efficiency is to co-locate plants with other cryogenic gases. such as LNG terminal, by utilising the cold energy from the LNG regassification to pre-cool the hydrogen before liquefaction.

The theoretical minimum energy required to liquefy hydrogen is about 2.88 kWh/kg, based on a reversible Carnot refrigeration cycle operating between ambient temperature and hydrogen's boiling point (20 K). The Carnot process assumes ideal, lossless heat exchange and perfectly efficient compression and expansion—conditions that are physically unattainable. In reality, practical limitations such as the irreversibility of compression, friction, heat leaks, and imperfect insulation mean that even the most advanced systems consume around 5–6 kWh/kg[22]. Current targets for the US and the EU lie around 6 kWh, over a 50% reduction in some cases, with the European IDEAliquid hydrogen project developing a scenario using real world supplier technology to theorise an energy intensity of 6.4kWh/kg in 2013[21]. The project looked at 30, 40 and 50tpd facilities operating at different loads to analyse if efficiency differences depending on capacities.

6.3 Storage & Distribution

6.3.1 Current Storage Models

Hydrogen can either be stored in large spherical cryogenic storage tanks as shown on page 33 or in smaller cylindrical tanks, depending on the application and the need for transportable storage. Large, market leading IGC's offer bespoke industrial sized models such as Air Liquide, who built NASA's 4,542,000L Spherical storage (321t), the largest model at the time. Whereas cylindrical models typically only have a maximum capacity of 64,000L (16,900 gallons or 5,000kg). Samsung C&T have been granted permission to build a 39,558,400L (2,800t) facility in South Korea which will dwarf any existing tanks[23] by a nearly 10-fold margin.[24]

Figure 9. Liquid hydrogen trailer[24]

[22] DOE Hydrogen and Fuel Cells Program Record. Department of Energy. Accessed at: https://www.hydrogen.energy.gov/pdfs/19001_hydrogen_liquefaction_costs.pdf (2019)
[23] Samsung C&T Newsroom. Samsung C&T develops design for world's largest liquefied hydrogen storage tank. Accessed at: https://news.samsungcnt.com/en/features/engineering-construction/2024-02-samsung-ct-develops-design-for-worlds-largest-liquefied-hydrogen-storage-tank/ (2024)
[24]Chart, Hylium form joint venture to supply liquid hydrogen trailers in the Republic of Korea, Gasword: https://www.gasworld.com/story/chart-hylium-form-joint-venture-to-supply-liquid-hydrogen-trailers-in-the-republic-of-korea/2093159.article/

The pressure inside these models is drastically different to that of gaseous models, ranging from atmospheric pressure up to around 8 bar, but have to be kept at -252.9°C, if the temperature increases then the hydrogen will gasify and quickly build the pressure up inside the tank. As a result, storage vessels are equipped with emergency pressure relief valves to ensure safety and to maintain the structural integrity of the cylinders or tanks. These tanks, depending on the materials used, distances travelled, and maximum capacities, can have a lifespan of c. 30 years (10,000-50,000 cycles) if regularly serviced. These figures are generally similar for both small cylindrical transportable storage and large-scale spherical industrial systems.

Costs for large, liquefied hydrogen storage tanks can range between 150-300 €/kgH2[26], meaning up to €1.5 million for a 5,000kg relocatable vessel. LH_2 storage tanks are also produced on a competitive and commercialised level led by industrial gas players such as Linde and Air Products, and closely connected liquid specialists such as Gardner Cryogenics.

6.3.2 Regional Distribution

Figure 10. A large-scale liquid hydrogen truck [26]

As discussed previously, distribution distance is one of the primary drivers for taking hydrogen to its liquid phase, hence its use in the US as the favoured method of distribution. The country's large geography means that gaseous hydrogen distribution and transmission options via tube trailer and gas pipelines have historically been limited and localised. Trucking utilising LH_2 trailers can transport payloads five to ten times greater than payloads of large-scale 250-450bar gaseous hydrogen trailers (c. 200 – 700kg). Historic common payload sizes are between 2,000-3,500kg of LH_2. However, innovation is still occurring, with Linde unveiling new trailers with a payload of 3900kg in 2025[25].[26]

There are several distribution methodologies LH_2 producers use to distribute their product. The main models for national distribution using road networks are:

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[25] Line Develops Europe's Largest Liquid Hydrogen Trailer to Tackle Supply Constraints. Fuel Cell Works. Accessed at: https://fuelcellsworks.com/2025/04/25/fuel-cells/linde-develops-europe-s-largest-liquid-hydrogen-trailer-to-tackle-supply-constraints (2025)

[26] Cryogenic Transport Trailers, Chart: https://www.chartindustries.com/Products/Cryogenic-Transport-Trailers

- **Milk round** – Linking multiple small customers together on one delivery round most commonly from a single hydrogen tanker
- **Point-to-point** – Focused full load distributed hydrogen to a single large-scale end-user before returning to base, refilling, and repeating
- **Hub-and-Spoke** – Larger 'hub' feeds a number of strategically placed 'spokes' optimised to local delivery distances and demand size
- **Nationalised systems** – nationally managed distribution infrastructure that can be accessed via connections and injection points

Each model has its own positives and negatives and are individually suited to either small, medium or large customers. Point-to-point is the dominant distribution model in nations like the US where the end-users are too far away from each other for multiple deliveries in one trip. The case is the same when it comes to serving one large-scale end user by maximising the amount of hydrogen distributed in relation to a single tanker, which is a common business model for several liquefaction plants. An example of this is the LH_2 contract between Air Products and NASA (see page 33). However, more densely customer populated areas such as the Northern Netherlands and regions of Germany, who are looking to increase their LH_2 applications, find different distribution models are more effective and efficient as multiple end users could be more proximally located or even collocated in hydrogen hubs. Therefore, European LH_2 users can frequently be more easily interconnected and benefit from milk-round style distribution systems, where a single tanker can service several end users in one trip. Optimising journey distances, route planning, and drop sizes to end users can be more efficient and yield increased profitability/lower prices. Recognising the potential benefit of LH_2 in Europe, the EU, through the Clean Hydrogen Partnership (CHP), has set goals to improve road-based LH_2 distribution. These targets, which include improving overall energy efficiency, and capital cost of equipment are detailed within the CHP's Strategic Research and Innovation Agenda 2021-2027[27].

[27] Strategic Research and Innovation Agenda 2021-2027. Clean Hydrogen Partnership. Accessed at: https://www.clean-hydrogen.europa.eu/document/download/8a35a59b-a689-4887-a25a-6607757bbd43_en?filename=Clean%20Hydrogen%20JU%20SRIA%20-%20approved%20by%20GB%20-%20clean%20for%20publication%20%28ID%2013246486%29.pdf (2022)

6.3.3 International Distribution

Figure 11. Kawasaki Heavy Industries – CG prototype for a commercial sized liquefied hydrogen carrier[28]

LH_2 has only recently become internationally traded as an energy vector, with the inaugural 1,250m³ shipment going from Australia to Japan in Q1 2022 highlighting the nascent nature of the market. This shipment, delivered on the Suiso Frontier vessel which was developed at a cost of $500m, is part of the Hydrogen Energy Supply Chain (HESC) project. HESC, an international collaboration between Japan and Australia, anticipates scaling the size of the project's next LH_2 vessel to 160,000m³ once in its commercial phase, 128 times larger than the Suiso Frontier. This increase would see 225,000 tonnes per year of LH_2 produced at the hydrogen liquefaction facility in Victoria and transported to Japan[28] by the mid-2030s. The project has also caught the attention of other nations around the world. In August 2023, the vessel toured Oman and other areas of the Middle East and Asia to showcase its capabilities and initialise imports to other locations. This has helped to set the foundations for other projects to develop seriously collaborations in this area such as Woodside and Keppel's conditional LH_2 offtake agreement between Australia and Singapore. The Middle East is an area of particular interest due to its potential as a major energy exporter, with LH_2 and Ammonia amongst the leading vector options considered to realise this. However, in November 2024, designs for the next phase of HESC have since been scaled back to support a vessel with capacity up to 40,000m³. The reason for this strategic alteration has been noted as a lower than expected demand for international transportation of LH_2.

This lower demand, however, has not stopped other projects from continuing to progress large-scale shipping vessel designs. TotalEnergies, in collaboration with GTT and LMG Marin, has secured approval in principle from Burea Veritas for a vessel with 150,000 m³ (10,500 tonnes) transportation capacity in February 2024. This milestone confirms the design, which features 120 times more LH_2 than the Suiso Frontier, is technically feasible and aligns with existing regulations. However, it should be noted that HESC's 160,000m³ design also managed this achievement prior to being scaled back[29].

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[28] Toward a new era of hydrogen energy: Suiso Frontier built by Japan's Kawaski Heavy Industries. Hydrogen Council. Accessed at: https://hydrogencouncil.com/en/toward-a-new-era-of-hydrogen-energy-suiso-frontier-built-by-japans-kawasaki-heavy-industries/ (2022)
[29] Oil giant TotalEnergies to co-develop the world's largest liquid-hydrogen carrier vessel. Hydrogen Insight. Accessed at: https://www.hydrogeninsight.com/innovation/oil-giant-totalenergies-to-co-develop-the-world-s-largest-liquid-hydrogen-carrier-vessel/2-1-1443046 (2023)

A number of International projects have also been investigating the potential of LH_2 supply pathways for European countries. H2Sines.Rdam, Europe's landmark project in this area until its cancellation due to lack of investment and defined regulation in April 2024, was seeking to establish a LH_2 supply chain between Sines, Portugal, and Rotterdam, Netherlands , at a scale of 100tpd [30]. Rotterdam, as one of Europe's critical energy ports, is still investigating how to develop the necessary supply chain and import infrastructure to support alternative projects and locations. Other LH_2 projects in the region, however, are still continuing to progress with alternative North West European ports identified as key landing locations due to their large-scale end-users. As such, in April 2025[31], a landmark Joint Development Agreement was announced to create a LH_2 supply corridor from Oman to the port of Amsterdam and Duisburg with Tata Steel Nederland seemingly acting as the value chain's primary bankable off-taker. The deal anticipates that the first volumes of LH_2 could arrive in Europe by 2029, with a potential annual volume of over 750,000t.

Import pathways, such as the long-distance routes mentioned above, could support EU hydrogen import targets (e.g. REPowerEU) at a competitive price by as early as 2030. Other notable countries, such as Morocco, are striving to become economically attractive production locations due to their high renewable energy availabilities, low domestic energy demand, and close geographic proximity to Europe. A recent techno-economic study by Aurora found that importing hydrogen in its liquid form is most economically viable distribution option over short-to-medium international distances, such as from Morocco to Germany[32]. This mirrors domestic analysis carried out within Germany where the long-term need for imports is recognised within its national energy and hydrogen strategies (est. 50-70% of national demand from foreign sources). To enable this, German ports will require the infrastructure to import, store, and regasify hydrogen derivatives for distribution to end users. Ports, such as Wilhelmshaven and Hamburg, are already positioning themselves to play this role – supporting developments from onshoring of local offshore renewable energy, to imports of international energy vectors.

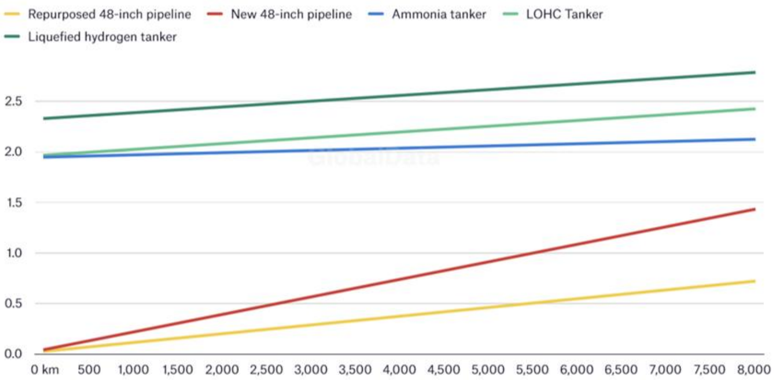
[30] ENGIE, a key player in the H2Sines Project. ENGIE. Accessed at: https://www.engie.com/en/news/H2Sines-Project (2022)

[31] Fuel Cell works. Tata Steel Nederland Joins Landmark Deal for First Oman-Europe liquid Hydrogen Corrdor. Accessed at : https://fuelcellsworks.com/2025/04/16/h2/tata-steel-nederland-joins-landmark-deal-for-first-oman-europe-liquid-hydrogen-corridor (2025).

[32] Aurora Energy Research. Renewable hydrogen imports could compete with EU production by 2030. Accessed at: https://auroraer.com/media/renewable-hydrogen-imports-could-compete-with-eu-production-by-2030/ (2023)

6.3.4 Cost and Alternative Energy Vectors

The drawback to moving hydrogen in its liquid form is that it is energy intensive to maintain the storage temperatures required and is thus expensive. Analysis by IEA estimates the levelised cost of distributing hydrogen by liquified hydrogen tankers is the most expensive of all energy vector possibilities at a cost of between $2.3-3/kg$_{2030}$ (see figure 12). New or repurposed gaseous pipelines are just <$0.2-1.5/kg[33] over the same distance. Therefore, justifying the development of LH_2 infrastructure is currently proving difficult unless within comprehensive value-chain-wide projects. One option to overcome this barrier, whilst supporting ongoing European energy developments is, to develop and retrofit LNG import terminals to become LH_2 and hydrogen-derivative-ready (ammonia, LH_2, or LOHCs). LNG imports have become a key option for the diversification of Europe's energy sources following the Russian invasion of Ukraine, with developments far exceeding the bloc's target to increase capacity to 50 bcm^3 by 2024. The low temperature liquefied nature of this energy source presents a significant opportunity to couple or transition infrastructure to other energy vectors with the same requirements. This would also significantly support the EU's RePowerEU targets of realising hydrogen imports by 2030.



Source: IEA Global Hydrogen Review 2022

	LH2	GH2	NH3 (liquid)	CH3OH
Volumetric Density	70.9 kg/m3	24.1-40.17 kg/m3 (350-700 bar)	682.6kg/m3	791.4kg/m3
Storage Conditions	Cryogenic Storage (-253°C)	Type 1-4 Cylinders (200-700 bar)	Standard tanks (-33°C)	Standard tanks (ambient temperature)
Safety	Flammable	Highly Flammable	Toxic, Flammable	Flammable, Toxic
2030 Levelised Cost	100 - 112 €/MWh	90-100 €/MWh	104 - 108 €/MWh	117 - 180 €/MWh
Gravimetric Energy Density	33.33kWh/kg	33.33kWh/kg	5.9kWh/kg	6.1kWh/kg

Figure 12. Levelised cost of delivering hydrogen by different methods in 2030 ($/kg hydrogen) and table comparing base properties of different energy vectors[20]

As shown in Figure 12, ammonia (NH_3) is a direct competitor to LH_2's potential as an energy vector. NH_3 can be stored as a liquid at just -33°C and is already transported internationally in commercial vessels with capacities of 60,000t (Hydrogen content ~10,000 t). This much larger scale of tanker, compared to current LH_2 vessels, enables more efficient shipped transportation of hydrogen (roughly 25% lower distributed cost compared to LH_2). Additionally, ammonia codes and standards around transport and handling are well established and known by major stakeholders, making it easier to establish new value chains and import terminals and therefore

[33] Why LNG terminals will not be transporting hydrogen any time soon. Energy Monitor. Accessed at: https://www.energymonitor.ai/tech/hydrogen/why-lng-terminals-will-not-be-transporting-hydrogen-any-time-soon/#catfish (2023)

faster to introduce. However, ammonia imports do require energy to 'crack' the NH_3 molecule back into hydrogen once landed, significantly reducing its efficiency. The cracking process can achieve, a best-case, efficiency of 76%[34] and creates an overall round-trip efficiency to the end user of just 15-30% from the original renewable energy feedstock captured[35]. These additional steps significantly increase the overall LCOH, discussed in further detail within the case study of this report.

6.4 Imports - The Role of Ports

Import of energy in all forms is required to achieve European net-zero targets, with ports emerging as critical infrastructure locations to realise this. For example, The Port of Rotterdam (PoR) is the energy hub for North Western Europe (NWE), with in and outbound energy flows totalling 8,800PJ, over three times the Netherland's national energy demand. In 2018, the Dutch government unveiled plans to develop 11.5 GW of offshore wind energy in the North Sea through their Roadmap Wind Energy at Sea 2030 plan. However, this target was increased to 18GW when the governments National Hydrogen plan was announced, aiming to have 4GW of electrolysis capacity by 2030. As such, PoR is scaling up hydrogen infrastructure to support the government's targets. It is expected that half of nation's hydrogen demand will be delivered via Rotterdam either through domestic production pipelined to shore, or imports (hydrogen, methanol, ammonia or LOHCs). Utilising this national momentum, the port and surrounding companies are developing a wide portfolio of projects capable of realising >1,000Kt of low-carbon hydrogen. Within this portolfio, a consortium of 18 companies has been assessing the opportunity to establish a world-scale ammonia cracker. This unit could deliver 1 million tonnes of green hydrogen per year for the decarbonisation of industry and mobility[36], for which a feasibility study was completed in 2023.

Similar energy developments have been occurring in Germany, particularly around Port of Wilhelmshaven (PoW) – the country's only deep-water port that can offer access to the largest vessel types. This has seen the port developed into one of the country's main LNG import locations where Uniper have deployed a repurposed FSRU which will regasify LNG from 70 tankers a year carrying 170,000m³ each, to then enter Germany's pipeline network. This terminal

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[34] Round-trip Efficiency of Ammonia as a Renewable Energy Transportation Media. Ammonia Energy. Accessed at: https://www.ammoniaenergy.org/articles/round-trip-efficiency-of-ammonia-as-a-renewable-energy-transportation-media/ (2017)

[35] Green ammonia fuel faces three big challenges. CRU. Accessed at: https://sustainability.crugroup.com/article/green-ammonia-fuel-faces-three-big-challenges#:~:text=That%20is%2C%2083%25%20of%20the,the%20ammonia%20to%20release%20hydrogen. (2022)

[36] Large-scale ammonia cracker to enable 1 million tonnes of hydrogen imports via port of Rotterdam. Port of Rotterdam. Accessed at: https://www.portofrotterdam.com/en/news-and-press-releases/large-scale-ammonia-cracker-to-enable-1-million-tonnes-of-hydrogen-imports (2022)

represents around two thirds of Germany's total LNG import capacity[37]. As well as LNG, The Green Wilhelmshaven project aims to transform the port into a green energy hub, utilising energy from 4GW of offshore wind combined with 1GW onshore electrolysis as well an ammonia import terminal. The import terminal will have an ammonia cracker to enable delivery of 300,000 metric tons of green hydrogen to be distributed from the location by 2030 - 10-20% of Germany's hydrogen demand by 2030[38]. Co-location of FSRU and ammonia, as envisaged at Wilhelmshaven, could hold significant replicability potential across Europe. At the end of 2023, there were 12 FSRUs across the EU with an import capacity of around 51mtpa/year, rising to 65mpta by mid-June 2024[39]. Many more planned FSRU projects are in development across France, Germany, Spain, Greece, and Italy which could potentially link regassification of other energy vectors.

Alongside this, the Port of Hamburg (PoH) is also investigating its ability to import hydrogen, with plans for it to become one of Germany's largest green energy import terminals, focused around ammonia import and distribution infrastructure. The planned terminal is to be located at Mabanaft's existing tank terminal and aims to provide cracked hydrogen to Germany in 2027-2028[40]. PoH's ambitions extend downstream within the Hamburg Green Hydrogen Hub which sets out plans to utilise decarbonised energy across the port economy, including cranes, shunting locomotives or trucks[41].

It is therefore clear to see that major ports around NWE are developing their ability to import and produce energies of the future. Whilst much of this has initially focused on LNG, offshore wind, and ammonia, ports are positioned as critical hubs to support the next phase of hydrogen introductions (gaseous and liquid). Recent activities have allowed development of the technical and commercial knowhow required to realise these value chains. Other, more nascent liquid and cryogenic fuels can make use of this progress to accelerate introduction into the wider energy landscape.

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[37] The Wilhelmshaven LNG terminal. LTeW. Accessed at: https://wilhelmshaven-lng.de/en

[38] Green Wilhelmshaven: To new horizons. Uniper. Accessed at: https://www.uniper.energy/solutions/energy-transformation-hubs/energy-transformation-hub-northwest/green-wilhelmshaven

[39] FSRU market thrives amid robust LNG demand growth. Drewry. Accessed at: https://www.drewry.co.uk/maritime-research-opinion-browser/maritime-research-opinions/fsru-market-thrives-amid-robust-lng-demand-growth#:~:text=Outlook%20of%20FSRUs%20in%20Europe,the%20end%20of%20this%20decade (2024)

[40] Hydrogen Central. Mabanaft successfully conducts scoping meeting for the construction of its planned ammonia import terminal in Hamburg. Accessed at: https://hydrogen-central.com/mabanaft-successfully-conducts-scoping-meeting-for-the-construction-of-its-planned-ammonia-import-terminal-in-hamburg/#google_vignette (2024).

[41] Hamburg Green Hydrogen Hub. Hamburger Energiewerke. Accessed at: https://www.hghh.eu/en#:~:text=The%20Hamburg%20Green%20Hydrogen%20Hub,production%20can%20start%20in%202025. (2025)

7 Liquid Hydrogen Applications

7.1 Aviation

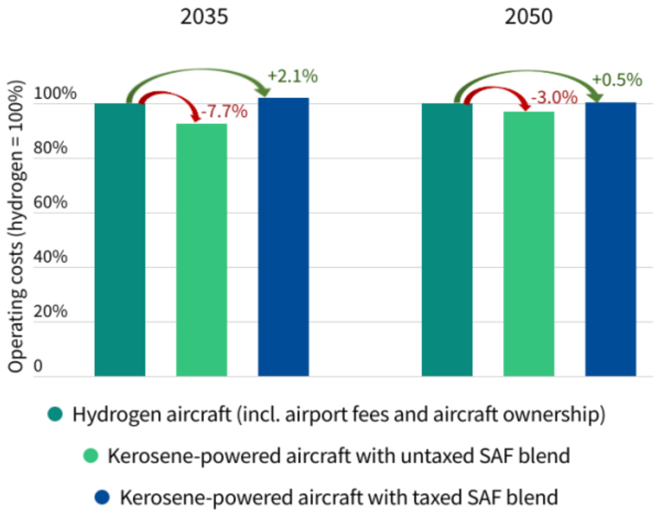

Figure 13. Operating costs of different aviation fuels[44]

In 2022, aviation accounted for 4% of the EU's total CO_2 emissions and 12% of the CO_2 emissions from the transport sector [42]. As such, decreasing aviation emissions will be a key aspect in achieving EU targets to reduce transport emissions by 90% by 2050 (compared to 1990 levels). However, net-zero aviation legislation and regulation, due to the phenomenal technical challenge of decarbonising flight, has been slow to be realised. Thus, the sector has, until recently, been focused on integration of economy-wide decarbonisation policies, such as the EU Emissions Trading System (ETS). This has led to a reduction in the sector's carbon footprint by >17 million tonnes per year so far. The legislation, which was adopted in 2008, was designed to apply to emissions from flights from, to and within the European Economic Area (EEA) – the EU Member States, plus Iceland, Liechtenstein and Norway[43] [44].

Despite these systems helping partially decarbonise the sector, acceleration is needed to significantly decrease the sector's emissions in line with the 55% economy-wide decrease envisaged within Fit-for-55. The International Aviation Trading Association, who represent over 330 airline and 80% of total aviation traffic, set out a draft of how its members will achieve net zero emissions by 2050. The outputs of this analysis can be found in Figure 14 showing the percentage split of differing decarbonisation solutions that will be required[45], highlighting the scale of required activity in the coming years.

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[42] European Aviation Environmental Report 2025. EASA Accessed at: https://www.easa.europa.eu/en/domains/environment/eaer (2025)
[43] Reducing emissions from aviation. European Commission. Accessed at: https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-aviation_en#:~:text=To%20achieve%20climate%20neutrality%2C%20the,to%20contribute%20to%20the%20reduction.
[44] Running a hydrogen plane could be cheaper than traditional aircraft by 2035, Transport & Environment Acced at: https://www.transportenvironment.org/articles/running-a-hydrogen-plane-could-be-cheaper-than-traditional-aircraft-by-2035
[45] IATA. Our Commitment to Fly Net Zero by 2050. Accessed at: https://www.iata.org/en/programs/environment/flynetzero/ (2024)

To support further emissions savings, the EU released the ReFuelEU aviation regulation in October 2023 which outlines sustainable fuel obligations. As such, members states must reach a minimum 70% use of sustainable aviation fuel (SAF) for flights departing the EU by 2050, with intermediate targets of 2% by 2025 and 5% by 2030[46]. This legislation provides much needed clarity to the sector to undertake decarbonisation projects with a higher degree of certainty that activities will comply with future sector developments.

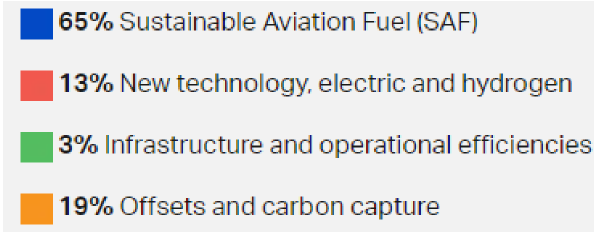

Figure 14. Fuel distribution for 2050 Net Zero[45]

New legislation coming into place and increases in carbon a kerosene taxes (USA increase to \$0.244 per gallon[47], Saudi Arabia and India also ~5% increase), has made alternative fuels more economically attractive. LH_2 is, currently, the only zero carbon and nitrogen emission fuel option for the aviation industry when used in a fuel cell. The aviation sector is building towards first commercial roll-out of LH_2 concepts by the mid-2030s for short to medium range routes of up to 3000km - roughly the same distance as a flight from the Netherlands to Cyprus. This range, alongside battery electric solutions for short-range options, would enable decarbonisation of air travel between almost all EU member states.


Figure 15. Airbus' Hydrogen propulsion concept planes[49]

Airbus has led the way in developing H2 concept aircraft. The company published three fuel cell powered concept planes in Q1 2022 to achieve the world's first zero-emission commercial flight by 2035 whilst simultaneously supporting hydrogen-combustion propulsion system [48]. After significant market engagement and development activities, AIRBUS have since streamlined their concepts to one model, reaffirming their commitment to LH_2 technology development in Q1 2025. The company is also investigating superconducting properties of LH_2 as a solution for propulsion systems, to

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[46] ReFuelEU Aviation. European Commission: Accessed at: https://transport.ec.europa.eu/transport-modes/air/environment/refueleu-aviation_en (2025)
[47] Using the Correct IRS No. on Form 720 - Kerosene Used in Aviation. IRS. Accessed at: https://www.irs.gov/businesses/small-businesses-self-employed/using-the-correct-irs-no-on-form-720-kerosene-used-in-aviation (2023)
[48] ZEROe. AirBus. Accessed at: https://www.airbus.com/en/innovation/low-carbon-aviation/hydrogen/zeroe (2023)

enable efficient high-power electrification of future hydrogen-powered aircraft. The demonstrator will mature a two megawatt-class superconducting electric propulsion system cooled by LH_2 via a helium recirculation loop in Toulouse, France, and Ottobrunn, Germany[49].

In 2019, before the global pandemic, the total fuel consumption of commercial airlines peaked at 95 billion gallons (decreased to 60bn gallons in 2021 and is again on the rise)[50]. Converting airports to support alternative fuels infrastructure will be expensive and require a complete transition of bunkering and refuelling both in terms of processes and safety regulations (e.g. allowing multiple fuel types on airfields at once). Airbus, seeking to support value chain wide introduction of hydrogen, are also exploring the changes that need to occur in this area via the GOLDIAT project. GOLDIAT received €10 million of EU Horizon funding to demonstrate small-scale LH_2 aircraft ground operations at three European airports[51]. This demonstration is the first step to address barriers to realising wider spread, and larger-scale introduction. For example, Kearney (2021) reported that filling up 30 percent of flights with hydrogen at Paris Orly Airport would require approx. 270 tons of LH_2 per day, assuming a consumption of 1.5 tons for a 1,500-kilometer flight for short-range, turboprop airplanes[52] (70 tankers around 10m³). This is an order of magnitude larger than current world-scale liquefaction plants and highlights how much progress is required to hydrogenise airports.

Whilst hydrogen is more gravimetrically dense than conventional jet fuel, it is much less volumetrically dense –one of the critical factors affecting the uptake of hydrogen in applications. For example, to achieve energetic parity with one litre of kerosene, four litres of LH_2 is required. This could be overcome by radically redesigning aircraft to accompany larger storage units without losing passenger capacity. However, long haul flights would likely be fuelled by SAFs. SAFs, which use hydrogen and biogenic sources of carbon to produce sustainable versions of existing jet fuels, are considered as 'drop in fuels', meaning they can be added into an aircraft's fuel mix with no changes needed to infrastructure or aircraft, allowing aviation companies to easily transition to more sustainable fuels whilst zero-emission technology is still being developed. SAFs

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[49] Airbus takes superconductivity research for hydrogen-powered aircraft a step further. Airbus. Accessed at: https://www.airbus.com/en/newsroom/press-releases/2024-05-airbus-takes-superconductivity-research-for-hydrogen-powered (2024)

[50] Total fuel consumption of commercial airlines worldwide between 2005 and 2021, with a forecast until 2023. Statista. Accessed at: https://www.statista.com/statistics/655057/fuel-consumption-of-airlines-worldwide/ (2022)

[51] Innovative aviation liquid hydrogen project launched. Airbus. Accessed at: https://www.airbus.com/en/newsroom/press-releases/2024-05-innovative-aviation-liquid-hydrogen-project-launched (2024)

[52] Aviation's hydrogen: the airport challenge. Kearney. Accessed at: https://www.kearney.com/industry/transportation-travel/article/-/insights/aviations-hydrogen-the-airport-challenge#:~:text=The%20levels%20of%20daily%20production,mixer%20truck%20at%20full%20capacity. (2021)

are typically blended with conventional fossil feedstocks to realise CO_2 emissions savings of up to 75%, but 100% SAF flights are starting to be trialled, as demonstrated by Airbus in March 2023[53].

Currently, one of the major challenges associated with the development of hydrogen-powered aviation, alongside the vehicles themselves, is the availability of fuel in both departure and arrival airport locations. To help tackle this issue, Airbus and ArianeGroup are developing the first LH_2 refuelling facility for Airbus' ZEROe aircraft at Toulouse, Blagnac airport in France. This demonstration project will be operational by 2025[54]. Replication of approaches such as this across Europe is necessary to achieve REFuelEU obligation targets. Replication of concepts in new geographies, however, is not just a technical barrier - the homogenisation of regulation across borders is required to realise seamless international operation. With the first hydrogen valley airport and joint initiatives on hydrogen with neighbouring countries such as Germany and Belgium, the Netherlands is well located to be one of the first to realise operation hydrogen-powered aircraft on short-to-medium-distance routes.

Figure 16. H2FLY aircraft[56]

ZeroAvia, an zero-emission aviation power train manufacturer, has already been testing a retro fitted aircraft with their prototype ZA600 hydrogen-electric engine which has completed a record breaking 10 flight test campaign in July 2023. As a result of this, ZeroAvia, whose concept is powered by gaseous hydrogen, have received a lot of interest from large firms such Airbus, Amazon, Barclays and Neom, raising over $150m across its funding rounds. With this, they plan to have a first commercial hydrogen-powered flight by 2025 and subsequently ramp up its

[53] AIRBUS. Airbus' most popular aircraft takes to the skies with 100% sustainable aviation fuel. Available at: https://www.airbus.com/en/newsroom/stories/2023-03-airbus-most-popular-aircraft-takes-to-the-skies-with-100-sustainable (2023).

[54] Airbus and ArianeGroup to pioneer liquid hydrogen technology. AIRBUS. Accessed at: https://www.airbus.com/en/newsroom/press-releases/2022-11-airbus-and-arianegroup-to-pioneer-liquid-hydrogen-technology (2022)

technology to power 40-80 seat flights by 2027[55]. Whereas German-based H2Fly have carried out the world's first liquid-hydrogen powered aviation flight for three hours on the 7th September 2023 in a demonstration using a fuel-cell propulsion system. This demonstration aircraft is believed to have a range of 1,500km and the firm are now looking to scale up their technology for regional aircraft and other applications following its success[56]. LH_2 in the aviation has sector has reached a TRL of 6 through industrially relevant demonstration flights.

7.2 Aerospace

NASA has been using LH_2 in their aerospace applications since 1954. LH_2 combined with liquid oxygen makes an extremely dense and powerful rocket fuel, which is why NASA continues to be scaling their volumes today. This is exemplified by their 2022 contract with Air Products worth approx. $75 million to supply 3.4 million kg of LH_2 to support operations at the Kennedy Space Centre and the Cape Canaveral Space Force Station. A portion of this LH_2 will be also used in applications supporting the development of hydrogen-powered aeronautics[57]. Due to this reliance on LH_2, NASA also boasts the world's largest spherical LH_2 cryogenic storage tank, capable of storing 370,000kg (1.25 million gallons).[58]

Figure 17. NASA's liquid hydrogen storage tank[58]

For context, the NASA space shuttle orbiter and external tank carries 720,000 kg of liquid propellent, including 103,000 kg of LH_2[59]. LH_2 is used as coolant in several aspects of the take-off process including pre-chilling fuel lines as well as in pre-chill operations for the Power Reactant Storage and Distribution System (PRSDS).[60]

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[55] Hydrogen aircraft start-up secures 'largest financing round to date' from Airbus, Amazon, Barclays, Neom and more. Hydrogen Insight. Accessed at: https://www.hydrogeninsight.com/transport/hydrogen-aircraft-start-up-secures-largest-financing-round-to-date-from-airbus-amazon-barclays-neom-and-more/2-1-1520161 (2023)
[56] 'World first' | German aviators fly liquid hydrogen-powered plane for three hours. Hydrogen Insight. Accessed at: https://www.hydrogeninsight.com/transport/world-first-german-aviators-fly-liquid-hydrogen-powered-plane-for-three-hours/2-1-1514524 (2023)
[57] NASA Awards Contract for Liquid Hydrogen. NASA. Accessed at: https://www.nasa.gov/press-release/nasa-awards-contract-for-liquid-hydrogen (2022)
[58] Kennedy Plays Critical Role in Large-Scale Liquid Hydrogen Tank Development, Fuel Cell Works. Accessed at: https://fuelcellsworks.com/news/kennedy-plays-critical-role-in-large-scale-liquid-hydrogen-tank-development
[59] The Space Shuttle. NASA. Accessed at: https://www.nasa.gov/reference/the-space-shuttle/
[60] NASA Space Shuttle: When was the final Shuttle launch? What happened to Shuttle Atlantis?, Express. Accessed at: https://www.express.co.uk/news/science/1156254/NASA-Space-Shuttle-final-launch-2011-when-was-shuttle-atlantis

Figure 18. NASA space shuttle[60]

NASA is also part of a consortium working on the Centre for High-efficiency Electrical Technologies for Aircraft (CHEETA), with the goal to develop, mature, and design disruptive technologies for electric commercial aviation. Part of the project will conduct a Design Study for Hydrogen Fuel Cell Powered Electric Aircraft using Cryogenic Hydrogen Storage[61]. Phase 1 of this project was completed in 2023, where simulations of the created concept achieved comparable performance to current 737-800 aircraft, whilst producing zero carbon dioxide and nitrogen oxide emissions.

Phase 2 will take the conceptual designs the group developed and create prototypes of key components and subsystems. This begins with the development of a scaled version of the envisaged hydrogen aviation power train with the potential to couple to superconducting technologies also assessed (expected peak power capacity in excess of 300 kW). As well as power production, the consortium are also investigating storage requirements of these vehicles, with designs for a 300-liter prototype tank to be realised. This will result in the production of a 5.5% scale aircraft to demonstrate and fully assess the benefits of liquid hydrogen fuelling.

Figure 19. Artist's rendering of an advanced commercial transport aircraft concept utilizing CHEETA systems[63]

NASA aren't the only space agency to utilise LH_2 in their rockets. In the 1970s, the European Space Agency (ESA) used LH_2 for the Ariane 1 rocket in its third propellent stage. The Ariane rockets, which had 11 successful launches between 1979 and 1986[62], are continuing to be developed with latest rocket designs for Ariane 6 investigated within the HyGuane project. Ariane 6, Europe's next generation launch vehicle, will continue to use LH_2 as part of its fuel load[63] with an anticipated

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[61] NASA Fuel Cell and Hydrogen Research Activities. NASA. Accessed at: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/review23/ia012_jakupca_2023_o-pdf.pdf (2023)
[62] Ariane 1, 2, 3. THE EUROPEAN SPACE AGENCY. Accessed at: https://www.esa.int/Enabling_Support/Space_Transportation/Ariane_1_2_32#:~:text=Altogether%2C%2011%20successful%20Ariane%2D1,three%20launchers%20were%20slightly%20different
[63] Liquid hydrogen storage for Ariane 6. THE EUROPEAN SPACE AGENCY. Accessed at: https://www.esa.int/ESA_Multimedia/Images/2020/12/Liquid_hydrogen_storage_for_Ariane_62 (2020)

storage volume of $28t_{H2}$ in its central tank. HyGuane, alongside technology development, assesses how the European Space Agency will green fuel supply (oxygen and hydrogen). The project will utilise French Guiana's distinct solar potential to produce 130 tonnes of green hydrogen per year from electrolysis by 2026[64] to feed liquid fuel requirements with excess hydrogen utilised to support additional vehicles and electricity generators.

7.3 Maritime

For the same reasons that LH_2 is becoming more attractive to the aviation industry, the maritime sector is also seeing an increase of activity in this area. Maritime is also predicted to become one of the primary ways of transporting LH_2 across the world to support international renewable energy value chains.

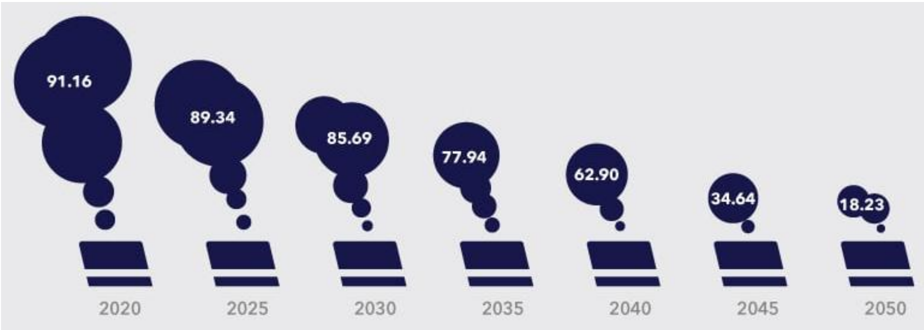

Figure 20. Required GHG intensity decreases envisaged by the FuelEU Maritime legislation – DNV[66]

The European maritime sector is now legally bound to decarbonise as part of the FuelEU Maritime Initiative as an additional arm of the EU's Fit for 55 package. Starting in 2025, the EU will impose time-bound reductions on the well-to-wake GHG intensity of maritime fleets. This includes 100% of all energy used on journeys and port calls within the EU/EEA, and 50% of energy used into or out of the same areas. These targeted reductions will start at 2% in 2025 increasing to 80% by 2050 compared to the 2020 levels (91.16gCO_2e/MJ baseline) [65]. The initiative also supports the uptake of renewable fuels of non-biological origin (RFNBO) - renewable liquid or gaseous transport fuels for which none of the energy content of the fuel comes from biological sources, including hydrogen. This is done via double counting the emissions saving potential of these fuels up to 2033 to encourage their development within the initial legislation period. If this does not

[64] Green hydrogen for Ariane 6 and more. The European Space Agency. Accessed at: https://www.esa.int/Enabling_Support/Space_Transportation/Green_hydrogen_for_Ariane_6_and_more (2023)
[65] FuelEU maritime initiative: Council adopts new law to decarbonise the maritime sector. European Council. Accessed at: https://www.consilium.europa.eu/en/press/press-releases/2023/07/25/fueleu-maritime-initiative-council-adopts-new-law-to-decarbonise-the-maritime-sector/ (2023)

sufficiently stimulate demand in this sector (i.e. if RFNBOs are <1% of total maritime energy consumption), then the commission will introduce what is known as a 'sunrise clause'. This will see a mandatory 2% RFNBO obligation introduced by 2034 to guarantee demand development. This is expected to be a cornerstone piece of legislation to drive demand for LH_2, and other hydrogen derived fuels.[66]

Figure 21. MF Hydra in Norway[67]

Prior to the ReFuel Maritime's introduction, a number of companies have already been investigating LH_2's potential in the sector. 2023 saw Norled champion deployment of the world's first LH_2 fuel cell passenger ferry in Norway, the MF Hydra[67], which can carry up to 300 passengers and 80 vehicles. The 82.4m long ferry is primarily powered by two 200kW Ballard fuel cells with an 80 m³ hydrogen storage tank to fuel them. Several companies' private endeavours have seen designs for more vessels developed including the French project - Energy Observer (EO). In 2022 EO unveiled a concept for a zero-emission cargo ship, which would be powered by 2.4MW of fuel cell power, fed from 1000m³ (70 tons) of LH_2 capable of a range of 4000 nautical miles[68]. The EO2 project, a follow-on from the original activities, was awarded EUR40 million in 2024 to encourage the development of clean technologies in sectors that are difficult to decarbonise[69]. The funding should enable the project to take a crucial step towards construction and operation of the intended 160m long vessel capable of carrying 1,100 TEU containers, now powered by an anticipated 4.8MW of fuel cells, with the goal of sailing in 2029.

Whilst LH_2 has only recently been considered as fuel in maritime vehicles, the maritime industry has been used to distribute LH_2 for a long time. NASA have been using tugged barges with storage capacities of 3000m³ of LH_2 to supply their operations since the 1960s and still use them today[70]. Whilst these barges aren't currently fuelled by LH_2 themselves, tug barges have

[66] Fuel EU Maritime, DNV. Accessed at: https://www.dnv.com/maritime/insights/topics/fueleu-maritime/
[67] Norled's MF Hydra achieves significant operational milestones, Ballard. Accessed at: https://blog.ballard.com/marine/norled-hydra-operational-milestones-ballard-fcwave
[68] Energy Observer unveils zero-emission, LH2-powered cargo ship concept. Offshore Energy. Accessed at: https://www.offshore-energy.biz/energy-observer-unveils-lh2-powered-cargo-ship-concept/ (2022)
[69] European Financial Boost For The Energy Observer 2 Cargo Ship. H2 Today. Accessed at: https://hydrogentoday.info/en/energy-observer-cargo-ship/ (2024)
[70] The role of liquid hydrogen in integrated energy systems–A case study for Germany. Busch, t, et al. Accessed at: https://www.sciencedirect.com/science/article/pii/S0360319923027222#:~:text=NASA%20also%20uses%20barges%20for,for%20overseas%20transport%20%5B30%5D. (2023)

significant potential to be switched in the future. Future Proof Shipping (FPS) has partnered with Nike to launch the first hydrogen powered inland container ships with the goal to accelerate Nike's zero-carbon emission and zero-waste targets. This project, called H2 Barge 1, runs on gaseous hydrogen and will reduce emissions by 2,000 tons of CO_2 a year operating primarily from the port of Rotterdam[71]. The potential to scale up fleet sizes and distances would likely call on either more regular refuelling points along routes, or require the greater density LH_2 fuelling can provide. The success of H2 Barge 1 has seen follow-on activities around a second retrofitted hydrogen-powered barge - H2 Barge 2 –launched in March 2024. The vessel is capable of carrying 190 TEU and has a total power output of 1.2MW, supplied by six fuel cell modules – similar to the

Figure 22. Antonie H_2 Powered Barge[72]

solution deployed on the first model.

Within HEAVENN and the associated WEVA project, a hydrogen powered barge has also been developed by Lenten Scheepvaart to demonstrate the viability of hydrogen-electric powertrains on inland waterways. The Antoine, built by Concordia Damen, completed a first operational trial in November 2023. The project has not only shown technological innovation but also set a lot of the foundations for future replication by other sector stakeholders across other areas. This includes working closely with third party bodies such as insurers, e.g. Lloyds register, to increase knowhow across all relevant areas. This barge will move salt for chemical producer Nobian on the Delfzijl-Botlek route[72].

Meanwhile, the H2ESTIA project, publicised for the first time in March 2025, has also announced an innovative design to develop the world's first LH_2 powered cargo ship. Key announced features of H2ESTIA include an integrated hydrogen propulsion system with a cryogenic hydrogen storage

[71] First inland hydrogen container ship launched by FPS and Nike. Hydrogen Fuel News. Accessed at: https://www.hydrogenfuelnews.com/inland-hydrogen-container-ship/8559014/ (2023)
[72] H2 Salt Barge. HEAVENN. Accessed at: https://heavenn.org/projects/salt-barge-boat/

and bunkering system for safe handling of LH_2 at extremely low temperatures. Initiated by Dutch innovation company NIM, this project is backed by the Dutch ministry of infrastructure and Water Management and managed by Van Dam Shipping[73], and could be critical to developing LH_2 demands in the coming years.

Methanol (CH_3OH) is another leading sustainable alternative fuel option rivalling LH_2, produced by combining green hydrogen with captured CO_2 that is a liquid at room temperature and pressure. It has higher volumetric density than LH_2 at 4.33 kWh/litre enabling much larger operational ranges, making methanol better suited to world-scale cargo ships and international shipping routes. Maersk has shown great interest in this e-fuel option with 25 methanol-enabled vessels on order to be delivered by 2027[74]. These ships feature dual engines allowing them to operate on both LNG and methanol as the clean fuel market develops. Therefore, LH_2's applicability to the maritime market is expected to be limited to a portion of the market featuring small-to-medium scale vehicles, and vessels transporting LH_2 itself. However, it should be noted that LH_2 can also be useful itself in the production of methanol at sufficient scales.

If LH_2 is to be transported on a international scale by maritime in the future, then ports will have to learn how to import and handle this hydrogen, as its estimated over 40% of all hydrogen demand in the EU could be located in port areas[75]. Major port locations already have knowledge with other vectors and liquid fuels such as ammonia and LNG, (e.g. Rotterdam, Hamburg and Wilhelmshaven), but few locations are experienced with LH_2. Development of this knowhow could have a positive effect on the use of LH_2 in maritime as well as other end uses in ports environments (e.g. port cranes, cold ironing). However, it should be noted that LH_2 refuelling and utilisation is specialist knowledge in standard markets, with use in the maritime industry even more niche. Further utilisation will require significant regulation, codes, and standards progress to facilitate, particularly within bunkering systems (e.g. investigated within Interreg H2SHIPS) and further enabling legislation akin to AFIR for road-based hydrogen demands.

[73] The Netherlands launches the H2ESTIA project to develop the world's first liquid hydrogen-powered cargo ship. Hydrogen Central. Accessed at: https://hydrogen-central.com/the-netherlands-launches-the-h2estia-project-to-develop-the-worlds-first-liquid-hydrogen-powered-cargo-ship/ (2025)
[74] 'Intolerable risk' Methanol winning the hydrogen shipping race as new studies highlight dangers of ammonia at sea. RECHARGE. Accessed at: https://www.rechargenews.com/energy-transition/intolerable-risk-methanol-winning-the-hydrogen-shipping-race-as-new-studies-highlight-dangers-of-ammonia-at-sea/2-1-1252452 (2022)
[75] Press release: Study on hydrogen in ports and industrial coastal areas. Clean Hydrogen Partnership. Accessed at: https://www.clean-hydrogen.europa.eu/media/news/press-release-study-hydrogen-ports-and-industrial-coastal-areas-2023-03-30_en#:~:text=According%20to%20the%20REPowerEU%20Plan,tonnes%20per%20year%20in%202030. (2023)

7.4 Heavy Duty Road Vehicles (HDVs)

Despite major improvements in fuel efficiency and reduced emissions from petrol and diesel vehicles, - lorries, buses and coaches are responsible for more than a quarter of GHG emissions from road transport in the EU, and over 6% of total EU GHG emissions. As a result, the EU developed the Regulation on CO_2 emission standards for heavy-duty vehicles in 2019. This regulation aimed to reduce emissions from new lorries by 15% in 2025 and 30% in 2030 compared to the reference period of July 2019 - June 2020. A revision of the regulation was made in May 2024, to enable a greater reduction of CO2 emissions per km from new HDVs by 90% by 2040, as compared to the same reference period, with intermediate targets for 2030 (45%) and 2035 (65%)[76].

Electric vehicles have been seen as the leading way to decarbonise road-based transport. However, adoption of electric HDVs faces challenges including long charge times, lower range than petrol and diesel equivalents, and below rated performance in geographies with high gradient routes and/or extremely low temperatures. Therefore, hydrogen fuel-cell electric, and internal combustion engine vehicles have become a leading decarbonisation option for this area of the economy. Hydrogen solutions feature a higher power-to-weight ratio compared to electric vehicles which enable larger ranges across similar refilling times to current diesel models. Hydrogen also provides the ability to operate these vehicles in more remote locations due to lack of need for electrical infrastructure. This is particularly relevant in the US, where the department of energy highlighted in their transportation decarbonisation blueprint in 2023 that hydrogen represents the greatest long-term decarbonisation potential for long-haul trucking compared to battery/electric and sustainable liquid fuels[77].

The majority of hydrogen vehicles in the current market feature gaseous hydrogen onboard storage as it is cheaper and more readily available. This includes Hyundai's 'XCIENT' Fuel Cell Truck, which is one of the most deployed fuel cell truck models with >100 units on the road collectively having driven >4 million miles (May 2023)[78]. However, some manufacturers are now looking towards LH_2 on-board storage as its density can lead to even further operational benefits.[79]

[76] Reducing CO_2 emissions from heavy-duty vehicles. European Commission. Accessed at: https://climate.ec.europa.eu/eu-action/transport/road-transport-reducing-co2-emissions-vehicles/reducing-co2-emissions-heavy-duty-vehicles_en (2023)

[77] The U.S. National Blueprint For Transportation Decarbonisation. DoE. Accessed at: https://www.energy.gov/sites/default/files/2023-01/the-us-national-blueprint-for-transportation-decarbonization.pdf

[78] Hyundai's fuel-cell dreams remain Xcient. SAE International. Accessed at: https://www.sae.org/news/2023/05/hyundai-fuel-cell-class-8-act-expo (2023)

[79] Hyundai H2 Truck, Hyundai. Accessed at: https://hyundaihm.com/en/our-truck/

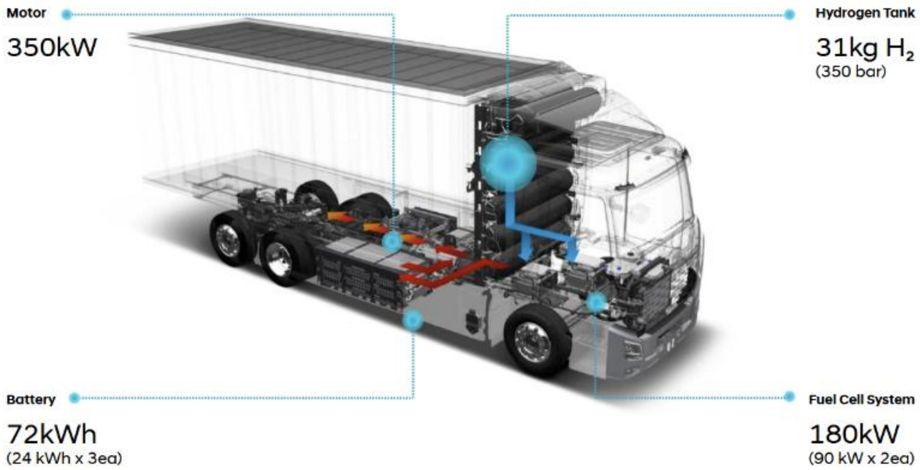

Figure 23. Hyundai XCIENT Fuel Cell Truck[79]

In September 2023, truck manufacturer Hyzon completed their first commercial trial of a LH_2 fuel cell electric vehicle, which made eight deliveries in Texas over a journey of >540 miles (870km) without refuelling. Hyzon are confident that their proprietary 200kW fuel cell system will be able to provide their trucks with a range between 650-800 miles, which is comparable to several diesel trucks[80]. The company's decision to develop a LH_2 focused powertrain is believed to be due to lower levelized cost of hydrogen into the fuel tank in comparison to the high-pressure gaseous hydrogen.

Daimler, parent company of Mercedes-Benz, have also developed a LH_2 truck called the GenH2, which is fuelled by two 40kg cryogenic LH_2 tanks giving it the capability to travel 1000km. This was proven in a demonstration where a GenH2 Truck covered a distance of 1,047 km between Woerth am Rhein and Berlin[81] on a single tank. Daimler have preferred to develop and use LH_2 over gaseous H2 because of its significantly higher density. Daimler Truck have the ambition to offer only new vehicles that are carbon-neutral in driving operation in its global core markets – with singular

Figure 24. Daimler Truck GenH2[85]

[80] Hyzon's first liquid hydrogen-fuelled truck travels 870km without refuelling in 16-hour test run. Hydrogen Insight. Accessed at: https://www.hydrogeninsight.com/transport/hyzons-first-liquid-hydrogen-fuelled-truck-travels-870km-without-refuelling-in-16-hour-test-run/2-1-1511791 (2023)

[81] Daimler Truck #HydrogenRecordRun: Mercedes-Benz GenH2 Truck cracks 1,000 kilometer mark with one fill of liquid hydrogen. Daimler Truck. Accessed at: https://www.daimlertruck.com/en/newsroom/pressrelease/daimler-truck-hydrogenrecordrun-mercedes-benz-genh2-truck-cracks-1000-kilometer-mark-with-one-fill-of-liquid-hydrogen-52369346 (2023)

orders for 100 GenH2 units to be supplied into Germany by 2026 already in place[82]. In 2021, Daimler signed an MoU with BP with the aim to collaborate on the development of the hydrogen refuelling infrastructure in the UK and introduction of their truck units. Partnerships such as this have enabled Daimler to realise customer trials in 2024, which include Air Products, who together were able to conduct real world testing of refuelling the Daimler trucks at Air products' HRS in Duisburg[83]. Whilst BP have agreed to undergo feasibility studies to design, construct, operate and supply a network of up to 25 hydrogen refuelling stations across the UK by 2030[84].[85]

LH_2 has the potential to support both the liquid and gaseous operational vehicles described above via new innovative technologies called Cryogenic Hydrogen Compressors (CHCs). CHCs can gasify LH_2 molecules to high pressures (>700 bar), requiring less energy in comparison to compressing low-pressure gaseous hydrogen to similar levels. These cryogenic pumps also feature a number of secondary benefits including a much smaller physical footprint, greater start/stop capabilities, and less noise pollution than gaseous analogues. CHCs, therefore, are expected to extend LH_2 infrastructure downstream onto customer refuelling sites to open its role within gaseous refuelling as well as conventional liquid operations. A simple design schematic of an LH_2 refuelling station can be found on page 69 in a cost comparison of a gaseous HRS' versus a liquid supplied station.[86]

Figure 25. Air Products CHC[86]

[82] FuelCellWorks. Faimler Truck Secures €226M in Government Funding for 100 Fuel Cell Trucks. Accessed at: https://fuelcellsworks.com/2025/01/06/clean-hydrogen/fallback-friday-daimler-truck-secures-226m-in-government-funding-for-100-fuel-cell-trucks (2025).

[83] Air Products Trials First Mercedes-Benz Genh2 Trucks as Part of Pioneering Project with Daimler Truck and Announces Plans for a European Hydrogen Refuelling Network. Air Products. Accessed at: https://www.airproducts.co.uk/company/news-center/2024/07/0725-air-products-trials-first-mercedes-benz-genh2-trucks-as-part-of-pioneering-project (2024)

[84] bp and Daimler Truck AG to accelerate the deployment of hydrogen infrastructure, supporting the decarbonization of UK freight transport. BP. Accessed at: https://www.bp.com/en/global/corporate/news-and-insights/press-releases/bp-and-daimler-truck-ag-to-accelerate-the-deployment-of-hydrogen-infrastructure.html (2021)

[85]Daimler Truck conducts first liquid hydrogen refueling with next-gen truck prototype, Auto Motive Testing Technology International. Accessed at: https://www.automotivetestingtechnologyinternational.com/news/fuel-cells/daimler-truck-conducts-first-liquid-hydrogen-refueling-with-next-gen-truck-prototype.html (2022)

[86] Cryogenic Hydrogen or Helium Compressor, Air Products. Accessed at: https://www.airproducts.co.uk/equipment/cryogenic-hydrogen-compressor

To incentivise hydrogen transport and ensure that fuel is readily available across Europe for HDVs the EU have developed the Alternative Fuels Infrastructure Regulation (AFIR). This requires member states to develop hydrogen refuelling stations capable of 1tpd of output every 200km and in every major urban node along the TEN-T corridor by 2030. The Netherlands is a key location along the TEN-T network as three of the corridors are linked through the region, including the North Sea - Baltic, North Sea – Mediterranean and Rhine – Alpine. Larger throughput stations will likely be required in critical areas such as Rotterdam, where multiple corridor networks connect. In previous drafts, AFIR has specifically mentioned requirements for LH_2 refuelling, showcasing the EU's expectation of the strategic importance of LH_2 in the road transport network. It is still expected that some AFIR stations will store hydrogen in its liquid form, where advantageous (high throughputs, or geographically disparate from supply sources thereby providing greater security of supply). Storage in liquid form can also reduce the amount of compression required to enable 700 bar refuelling if regasifying which could enhance operational efficiencies at some locations. For instance, a refuelling station being developed by Air Products in the Port of Zeebrugge (Belgium) will utilise LH_2 storage – likely due to the ability to directly utilise imported supply pathways. This station will be the first in Europe with LH_2 storage[87].[88]

Figure 26. Netherlands TEN-T corridor links[88]

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[87] Europe's First Liquid Hydrogen Refueling Station Takes Shape. Energy News. Accessed at: https://energynews.biz/europes-first-liquid-hydrogen-refueling-station-takes-shape/#:~:text=The%20development%20of%20Europe's%20first,future%20of%20hydrogen%2Dpowered%20trucks. (2023)

[88] TENTtec interactive map, European Comission. Accessed at: https://webgate.ec.europa.eu/tentec-maps/web/public/screen/home (2025)

7.5 Electronics Manufacturing

LH_2 has also be used in many electronics manufacturing processes as a form of high purity hydrogen[89], which is required within the production of wafers and other components. The purification stages involved within the overall liquefaction process (page 14) removes unwanted molecules which will not liquefy. This hydrogen can then be utilised directly in liquid form as an additional process coolant, but is typically re-gasified for use in the electronics industry its operations.

Figure 27. A semiconductor[93]

Hydrogen can be used in semiconductor, display, LED and photovoltaic segments of this industry. Within semiconductor manufacturing, hydrogen plays several important roles, this includes: Cleaning of wafers to removing impurities that could affect performance; heating and cooling the wafers more efficiently to improve quality and saving energy (annealing); selectively removes certain materials from the wafer surface, reducing waste (etching); behaving as a carrier gas to help introduce other atoms that fine-tune the electrical properties of the chips (doping). Alongside these, hydrogen can also be used to support epitaxy, deposition and stabilising.

Semiconductors are a key component for electronic devices, enabling advanced communications, and computing, used across healthcare, military, transportation, smart control systems in clean energy and many other applications. As a result of this widespread application, 1.15 trillion semiconductor units were shipped in 2021[90]. The world's largest semiconductor equipment supplier is ASML, based in the Netherlands. Several nations around the world are beginning to develop their own local manufacturing facilities to ensure security of supply case of critical failures or geopolitical events, as was demonstrated within COVID with overreliance on Chinese-based solutions. This is exemplified by developments such as the US Department of

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89 Ultra high purity hydrogen gas supply system with liquid hydrogen. Miyazaki, J, et al. Accessed at: https://www.sciencedirect.com/science/article/pii/036031999500100X (1996)

90 10 LARGEST SEMICONDUCTOR COMPANIES IN THE WORLD. ZIPPIA. Accessed at: https://www.zippia.com/advice/largest-semiconductor-companies-world/#:~:text=1.15%20trillion%20semiconductor%20units%20were,CAGR%20of%206.21%25%20through%202031. (2023)

Commerce's CHIPS programme. Announced in Q1 2025, CHIPS is a $1.4bn initiative to expand semiconductor manufacturing and packaging capabilities domestically in the US instead of relying on imports[91]. This will therefore create higher demands of LH_2 on a global scale. A 2024 report estimates that the USA utilises around 200 tons per day of LH_2 in semiconductor manufacturing, a significant portion of their total production, the same can be said for Europe's LH_2 market[92]. However, whilst the electronics industry makes up a considerable proportion of LH_2 demand, it represents <1% of total global hydrogen demand.[93]

7.6 Cooling for Superconductors

LH_2 is regarded as one of the most efficient coolants in cryogenics and is therefore particularly well suited in the use of within superconducting applications – a unique property where materials can conduct DC electricity without energy loss when below critical temperature. The potential of other elements, such as helium, have previously been explored for this purpose but it is much less abundant and requires very low temperatures (-269 ^{o}C), with nitrogen also explored both primarily due to their inert properties. LH_2 has been pursued as a promising alternative to these two options.

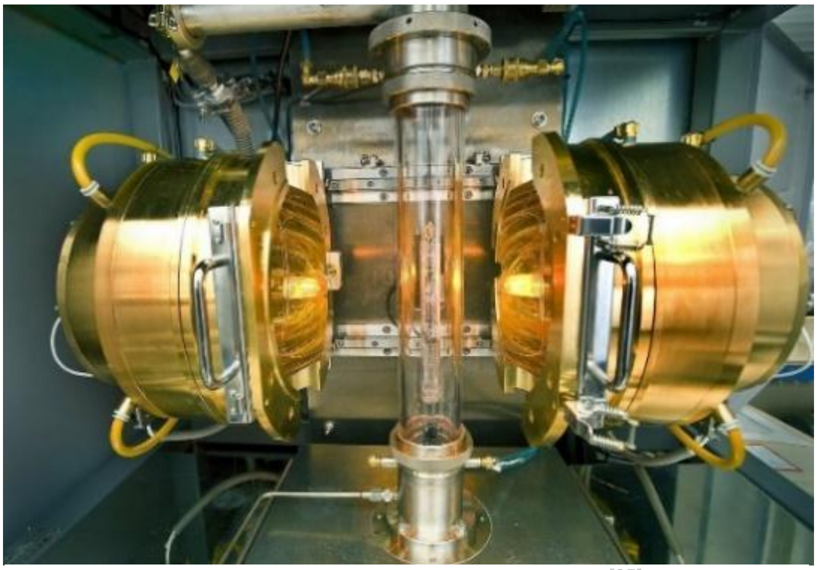

Figure 28. Superconducting magnet[95]

[91] The Surprising Role of Hydrogen in the US Semiconductor Boom. Hydrogen Fuel News. Accessed news: https://www.hydrogenfuelnews.com/hydrogen-us-semiconductor-boom/8569277/ (2025)
[92] What is Hydrogen Used For? CleanEpic Advising. Accessed at: https://www.cleanepic.io/blog/hydrogen-current-uses
[93] Semiconductors: What a deep dive into Cambridge's microchips sector can tell us about how our ecosystem creates and scales world-leading innovation, Cambridge Ahead. Accessed at: https://cambridgeahead.co.uk/news-insights/2024/semiconductors-what-a-deep-dive-into-cambridges-microchips-sector-can-tell-us-about-how-our-ecosystem-creates-and-scales-world-leading-innovation/

The coupling of low-temperature superconducting materials with magnets has already been used in various applications such as MRI instruments in hospitals, NMR spectrometers, mass spectrometers, fusion reactors and particle accelerators, showcasing its importance across the cutting-edge areas of science. During operation, superconductors must be cooled to cryogenic temperatures, in this state, the wire has no electrical resistance and therefore can conduct far greater electrical currents than ordinary wire, creating great magnetic fields. Superconductors have the potential to completely disrupt current electrical infrastructure due to their unique properties. However, at this stage in their development lifecycles, there is significant innovation and development that must occur to see widespread deployment therefore making current demand from this area is small. The best indication currently to the sector's growth potential are market reports which expect the area to almost triple in size across the next decade from a value of $6.8 billion in 2022, to $17.4 billion in 2032[94].[95]

8 Current Liquid Hydrogen Market Barriers

Whilst LH_2 is seen to have many application opportunities, with innovative technologies in development across a number of sectors, lack of currently bankable demand is a significant development barrier inhibiting the sector's development. For example, in 2023, Equinor and Air Liquide's landmark 'Aurora' project, which aimed to develop LH_2 supply chains for the maritime industry, was permanently scrapped after failing to attract customers across two years[96]. The project, which was to produce around six tonnes of LH_2 per day via electrolysis, stated that market conditions were not sufficient to drive stakeholders to LH_2 due to lack of government support and clear uptake mechanisms. It is unclear whether the introduction of RED III and FuelEU Maritime legislation would have provided sufficient impetus to now progress these activities. These legislative measures have helped to identify that RFNBOs will play a role within the EU's future energy mix, however, there still remains an ambiguity as to the preferred fuel-types within each

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[94] Superconductors Market. Allied Market Research. Accessed at: https://www.alliedmarketresearch.com/superconductors-market-A74562#:~:text=The%20global%20superconductors%20market%20was,10%25%20from%202023%20to%202032. (2023)

[95] Revolutionary superconducting magnet plate design and analysis, Phys.org. Accessed at: https://phys.org/news/2020-12-revolutionary-superconducting-magnet-plate-analysis.html

[96] Equinor and Air Liquide permanently scrap landmark liquified hydrogen shipping project after failing to attract customers in two years. Hydrogen Insight. Accessed at: https://www.hydrogeninsight.com/transport/equinor-and-air-liquide-permanently-scrap-landmark-liquified-hydrogen-shipping-project-after-failing-to-attract-customers-in-two-years/2-1-1415977 (2023)

market segment. This is particularly relevant to the medium-to-long-term markets of aviation and maritime where a number of fuels are competing to obtain development support and market share – e.g. hydrogen, e-methanol, ammonia, e-SAF amongst others. This uncertainly will harm end-user confidence, preventing and delaying investment decisions, and ultimately slowing achievement of net zero and the EU's decarbonisation and obligation targets. The EU have achieved greater certainty within the road-transport market via the required establishment of hydrogen infrastructure within AFIR. Similar Commission-led developments could be introduced to provide this clarification for other sectors, or member states could state their own preferences within their own individualised transpositions of RED III. These transpositions, however, must occur imminently, with only two member states achieving the May 21 2025 deadline for introduction set by the commission.

One of the other most significant factors blocking LH_2 developments is lack of knowhow and confidence. Currently, technical and operational understanding of the LH_2 value chain is locked within a few key sector players – primarily gas majors such as Air Products, Air Liquide, Linde or closely associated companies such as Gardner Cryogenics. This has caused the sector be highly specialised across key components (e.g. liquefier cold boxes and storage vessels/tankers), rather than a more widespread position as is exhibited with gaseous analogues. This creates significant first-mover disadvantage when opening a new market, as accessing these equipment pieces, prior to manufacturing at economies of scale, incurs significant cost and supply chain reliance due to reduced suppliers. Therefore, support, whether that be for value chain development, or the establishment of new innovative suppliers, is required to increase competitiveness and improve costs across the liquid value chain.

9 Future Liquid Hydrogen Developments

With industries such as aviation, maritime and long distance HDVs expected to realise demand increases for LH_2 in the coming years, there is need for new hydrogen liquefaction plants to support these sectors. However, in order to reach long-term decarbonisation goals, liquefaction facilities will need to be scaled up by an order of magnitude compared to today's large-scale plants, which sit around 30tpd. South Korea has taken steps to scale domestic capabilities facilities via construction of a 90tpd (30,000 tonnes per annum) plant to power its transport sector and position themselves as a world leader[97]. The LH_2 produced from this facility, which will be the largest in the world, will fuel hydrogen refuelling stations for South Korea's considerable FCEV fleets. The country, who had a global market share of 47.9% of new FCEV sales in 2023[98], laid out significant ambitions to increase vehicle uptake within their national hydrogen strategy[99] including 120,000 trucks by 2040. To support this demand, the government also laid out aims to realise 70 LH_2 refuelling stations by 2030[99]. However, a 90tpd liquefaction facility will not produce enough LH_2 to meet the country's envisaged demands, hence the strategy also includes intentions to realise a 100,000tpy LH_2 import terminal to acquire suitable volumes from international value chains.

Having been published in 2019, the majority of goals within South Korea's national hydrogen strategy are likely to be overestimated due to the sector's progression since. However, LH_2 remains a high priority for the government. The Ministry of Trade, Industry and Energy, announced in May 2025 it will establish a public-private task force, backed by ~€35m, to develop large-scale LH_2 carrying vessels by 2027. This compliments already announced plans (December 2024) to develop the 'Hydrogen Ocean K' LH_2 carrier vessel by the end of 2028, as well as other supply chain subsidies for road-based LH_2 distribution tankers which were also announced in May 2025.

Within the EU, whilst little legislation has been introduced specific to LH_2 sector development, several regulated plans have been set out around the long-term development of the hydrogen sector across 2030 and 2050. This includes the REPowerEU plan, which states that the EU will import 10 million tonnes of hydrogen by 2030. Whilst pipelines are expected to be the leading means of import to facilitate achievement of this goal due to their low cost and reliability (e.g. target could feasibly be met by ~five 1.9Mtpa routes from ideal geographies), it is expected that shipped imports will also make up a proportion of the total in order to diversify supply chains and access low-cost products from other geographies (e.g. Chile, Middle East[20]). As such, the IEA estimates that >10 LH_2 tankers and four 1 Mtpa LH_2 import terminals will needed to meet these targets, supported by three 1.9Mtpa pipelines in a hybrid approach. This diversification of clean energy, is not only a key part of RePowerEU, but also is a key goal of EU's competitiveness compass and Clean Industrial Deal, with the aim to reduce dependencies on individual volatile

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[97] Air Liquide hydrogen activities are accelerating in South Korea as demand is growing fast. Air Liquide. Accessed at: https://www.airliquide.com/group/press-releases-news/2021-07-27/air-liquide-hydrogen-activities-are-accelerating-south-korea-demand-growing-fast (2021)
[98] Global sales of hydrogen-powered vehicles fall by 11.5% in first four months of 2023. Hydrogen Insight. Accessed at: https://www.hydrogeninsight.com/transport/global-sales-of-hydrogen-powered-vehicles-fall-by-11-5-in-first-four-months-of-2023/2-1-1466755 (2023)
[99] South Korea outlines hydrogen roadmap to boost industry. Argus. Accessed at: https://www.argusmedia.com/en/news/2389672-south-korea-outlines-hydrogen-roadmap-to-boost-industry (2022)

locations. Therefore, different supply pathways, such as imported LH_2, is needed to support a more energy secure landscape on a whole-systems basis.

Liquefaction of gaseous energy is becoming increasingly important to the European energy landscape due to its array of different distribution methods and applications. However, large-scale LH_2 projects are not expected to be operational until 2030-35. One industry from which LH_2 could take significant learnings from is liquefied natural gas (LNG). From the first LNG shipment in 1989, LNG now accounts for 10% of global fossil gas demand[100]. LNG allows significant volumes of natural gas to be transported around the globe, where pipelines are unable to connect nations such as supply from the middle east to Asia, Europe and parts of Africa. Middle Eastern regions such as Saudi Arabia, who have a rich and significant oil and gas export industry are also keen to green their supply routes and first positioned LNG as a cleaner product than oil. Liquefaction of natural gas has played an important role in Europe since the Russian invasion of Ukraine. RePowerEU, alongside promoting hydrogen import, has supported development of LNG import capabilities as a mechanism to reduce dependence on Russian pipelines for gas and oil. This has successfully broadened knowledge of liquefied energy to a greater number of European locations. However, it should be noted that LNG is still has the potential to be highly emitting. Not only does natural gas still have intrinsic CO_2 emissions when burnt, but methane leakages can cause this energy vector to have a substantially higher environmental impact, as methane has 44 times the global warming potential of CO_2. Therefore, locations which have developed LNG experience are seeking to either co-develop or transition towards hydrogen derivative capabilities, including LH_2, due to a high degree of directly transferable knowledge including cryogenic cooling & storage.

Despite LNG's emission position, it is likely that significant volumes will still be required by 2050 – for instance McKinsey's global gas outlook to 2050[101], suggests that LNG demand will only peak in 2046. Due to this, it's reasonable to examine opportunities to improve the emissions, and environmental impact of LNG systems via co-location with other technologies. It has previously been highlighted by the IDEALH_2 project that significant efficiency advantages can be achieved through co-located production of both LH_2 and LNG via waste-heat utilisation and effective symbiotic use of certain sub-systems and processes – particularly two-stage helium reverse Brayton cycles. The integration of LNG and LH_2 production using a two-stage helium reverse Brayton cycle significantly enhances efficiency. This method leverages helium's superior thermodynamic properties to achieve low temperatures required for both LNG and hydrogen

[100] The Future of Hydrogen. International Energy Agency. 2019. Accessed at: https://www.iea.org/reports/the-future-of-hydrogen

[101] McKinsey. Global gas Outlook to 2050. (2021). https://www.mckinsey.com/~/media/mckinsey/industries/oil%20and%20gas/our%20insights/global%20gas%20outlook%20to%202050/global%20gas%20outlook%202050_final.pdf

liquefaction. Studies show that such integration can reduce specific energy consumption by approximately 10.67% and increase energy efficiency by around 6.63% compared to traditional separate production methods. This co-production approach not only optimizes energy use but also lowers operational costs and capital investment by sharing infrastructure and equipment[102].

10 Deploying Liquid Hydrogen in The Northern Netherlands

The Netherlands is one of the premier LH_2 nations in Europe. It is home to one of Europe's first liquefaction locations – a 5 tpd location open since 1987 – and continues to be a leading choice for further development, with a second plant to be opened in 2025 by Air Products. Once operational, the country will be home to more than half of Europe's liquefaction capacity, with both sites located in the Botlek area of Rotterdam. This highlights that the experience held in the nation is sufficient not only to support existing developments but also to facilitate cornerstone expansions of infrastructure to progress the sector to its next phase. The LH_2 produced at the existing site is used to supply the demands from high tech industries, with future volumes facilitating increases in this sector as well as initial expansions into the mobility market for large refuelling stations, heavy-duty road vehicles, and initial deployments in the maritime sector. However, such is the capital and operational expense associated these facilities that the hydrogen product will be mostly or fully committed prior to development to ensure sufficient business cases. This provides little opportunity to enable further organic demand development from the sectors noted above. Therefore, greater volumes of LH_2 are required to facilitate sector scaling which could be met via of further local liquefaction capacity, or via international imports.

10.1 Local Overview

One such area which could be ideal for further liquefaction development within the Netherlands is Delfzijl. The location presents a highly strategic opportunity for the development of a hydrogen liquefaction facility, due to its well established Chemical Cluster with high levels of existing hydrogen demands and knowhow, as well as its proximity to the Port of Eemshaven with its significant renewable potential. Both these stakeholders have been actively assessing and expanding their capabilities to support net-zero commitments especially in the area of hydrogen. The region also has access to low-cost renewable energy from existing sources such as a

[102] Optimization and Analysis of an Integrated Liquefaction Process for Hydrogen and Natural Gas Utilizing Mixed Refrigerant Pre-Cooling. MDPI. Accessed at: https://www.mdpi.com/1996-1073/16/10/4239 (2023)

62.7MW onshore wind power plant[103] and a 17.5MW solar park[104]in Groningen, and will gain access to even greater offshore energies from 2027 onwards. Construction of liquefaction facility in this region could utilise immediate industrial hydrogen needs to develop a commercial baseload whilst providing a foundational driver for the broadening geographic access to LH_2 from the current Dutch nucleus of Rotterdam. This could simultaneously provide sufficient demand development and interest in LH_2 to facilitate acquisition of even greater volumes via import from Eemshaven, positioning the port as a key energy terminal for European benefit.

The region's importance is further underlined by HEAVENN, which has played a central role in the development of the Northern Netherland's hydrogen sector. The project continues to support activities associated with local industrial, heavy-duty mobility, and inland waterway demands, with Delfzijl seen as a critical to all three application areas. As the sector continues to develop, enhancing reliability and resilience of supply and preparing for future demands from innovative sectors becomes increasingly important. This makes Delfzijl a natural choice for locating a liquefaction facility, either within the port zone or integrated into the chemical cluster itself.

10.2 Import Overview

An alternative option to liquefying locally produced hydrogen is developing a hydrogen import terminal at one of the regions' port locations. Hydrogen supplies from international chains can then directly feed local liquefaction facilities, or, if already in the form of LH_2, be placed directly into the market.

On a financial level, import of hydrogen and its derivatives can be highly competitive with local production in Europe due to advantageous renewable capacity factors. A report from Aurora energy research (2023[35]), found that imports of renewable hydrogen from Morocco, transported via ship in liquid form to Germany, could be delivered at a cost of just €4.58/kgH2. This is not only cheaper than other hydrogen derivatives from the same location (LOHCs €4.68/kgH2, Ammonia €4.72/kgH2) but is also potentially cheaper than local production of green gaseous hydrogen. Although there remains a significant trade-off with the security of the value chain due to its significant increase in length and complexity. Furthermore, A 2022 study by Kolb et al. from Friedrich-Alexander University (FAU) in Germany identified that not only could there be a cost benefit, but also a potential emissions benefit to these international value chains. LCA analysis carried out identified that areas with very high wind and solar capacity factors including Chile,

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[103] Power plant profile: Delfzijl Noord, Netherlands. Power technology. Accessed at: https://www.power-technology.com/data-insights/power-plant-profile-delfzijl-noord-netherlands/ (2024)
[104] Powerplant profile: Zonnepark Delfzijl Solar PV Park, Netherlands. Power Technology. Accessed at: https://www.power-technology.com/data-insights/power-plant-profile-zonnepark-delfzijl-solar-pv-park-netherlands-2/ (2024)

Canada, and Morocco[105], could achieve comparable or lower delivered emissions than local production pathways such as those from offshore wind around the port of Hamburg.

In the long-term there will be a need for both imported LH_2 and domestically produced LH_2. Localised production will be needed to initialise demand value chains and should be prioritised due to its high resilience and ability to enhance European technological innovation. However, local production will not be able to provide sufficient quantities to meet the goals of EU legislation. Thus, imports provide access to much greater volumes to support more widespread development of demand for dedicated supply to highly energy intensive industries, which have the ability to consume more capacity than current global liquefaction capabilities.[106] [107]

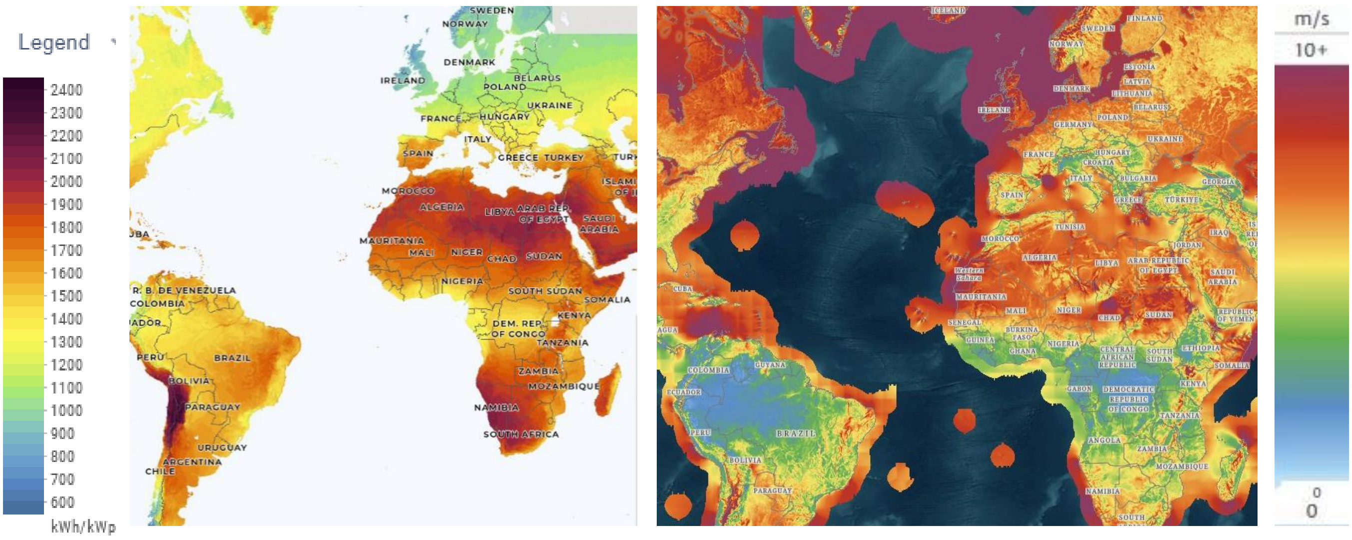

Figure 29. Left: Solar Capacity Factor across Europe, Africa and South America[106]
Right: Mean Wind Speed Across Europe, Africa and South America, at 100m [107]

[105] Kolb et al. Renewable hydrogen imports for the German energy transition - A comparative life cycle assessment. Journal of Cleaner Production. Accessed at: https://doi.org/10.1016/j.jclepro.2022.133289 (2022)
[106] Global Solar Atlas, EnergyData.info. Accessed at: https://globalsolaratlas.info/map
[107] Global Wind Atlas, EnergyData.info. Accessed at: https://globalwindatlas.info/en/

CASE STUDY

11 Potential for a Northern Netherlands LH_2 Facility

11.1 Norther Netherlands Case Study

Current trends in the sector indicate that the majority of hydrogen flowing through Europe will be handled at ports, both from offshore production and an international import basis. Rotterdam has had an operating liquefaction plant since 1987 with plans for its expansion to come online in the next 12 months. Port of Amsterdam is considering LH_2 imports to support its steel businesses. Delfzijl is also considered an ideal location for a hydrogen liquefaction facility, as the city is home to a chemical cluster, providing a skilled workforce with hydrogen application experience and is nearby the Port of Eemshaven which has plans to increase hydrogen production. Such a liquefaction facility or hydrogen import terminal at the port, will also help the EU reach its hydrogen targets and add energy security to the Northern Netherlands region. This, when combined with the importance of the HEAVENN hydrogen valley in leading Europe's hydrogen energy development, creates a potentially interesting context for a future LH_2 investment in the Northern Netherlands.

The following section explores the potential opportunity and provides overviews of: (1) establishment of local liquefaction capabilities centred around local North Sea renewables availability and (2) hydrogen import pathways connecting to infrastructure developed in the Port of Eemshaven area.

11.1.1 Industrial Demand

The Delfzijl Chemical Cluster, located in eastern Groningen, is one of the five major chemical production hubs in the Netherlands. It is home to 18 companies that produce a diverse range of industrial compounds such as salt, chloride, biobased plastics, fertilizers, and methanol. These outputs are vital to several key sectors, including transport, manufacturing, and agriculture. With its sustainable energy supply - sourced from wind turbines and biomass - and its strategic position

Figure 30. Delfzijl Chemical Cluster[108]

surrounded by an extensive agricultural hinterland, the cluster is evolving into a prominent North-West European centre for biobased industrial chemistry. Delfzijl/Eemshaven has become a key location for future hydrogen and renewables sector development emphasised by the HEAVENN Hydrogen Valley's activities.[108]

Hydrogen is already a cornerstone of activity within the cluster, with 3,500 tonnes of by-product hydrogen generated every year from the chlor-alkali process operated by Nobian. Existing cross-industry collaboration within the cluster further enhances resource efficiency, with this hydrogen already integrated into a cluster pipeline network and used as a feedstock or energy source. In addition, there are other potential new applications where hydrogen is being used for green energy applications. For instance, SkyNRG plans to produce 100,000 tonnes of sustainable aviation fuel (SAF) annually, using hydrogen as a primary feedstock. This process will also yield 35,000 tonnes of sustainable by-products such as LPG and naphtha, resulting in an 85% reduction in CO_2 emissions compared to conventional jet fuel. Additionally, the production of base chemicals like hydrogen peroxide (Evonik) and methanol (OCI Methanol Europe), amounting to several hundred thousand tonnes annually, offers significant short-term decarbonisation opportunities through the replacement of grey hydrogen with green alternatives.

Looking ahead, several large-scale electrolysers are planned in the region, securing a consistent supply of low-carbon hydrogen, ideal for conversion into liquid form. LH_2, in turn, can serve multiple strategic functions in the cluster. As a high-density energy carrier, it enables large-scale storage of surplus green hydrogen generated during periods of high energy prices, to realise an overall lower annual cost on a full system basis. This stored hydrogen can also be used to stabilise supply during times of low wind or solar generation, strengthening the cluster's energy security and operational reliability.

Importantly, LH_2 offers an ultra-pure form of the element, which is essential for sensitive chemical processes and energy production via fuel cells. This level of purity is harder to maintain in gaseous hydrogen over long distribution chains, making local liquefaction even more valuable. By offering both a scalable storage medium and a high-quality hydrogen source, LH_2 stands to play a critical role in supporting the cluster's decarbonisation and growth, while laying the groundwork for potential expansion into hydrogen-fuelled mobility and export markets.

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[108] Northern consortium contributes € 30 million Avantium builds FDCA flagship plant in Delfzijl, Agro & Chemistry. Accessed at: https://www.agro-chemistry.com/news/avantium-builds-fdca-flagship-plant-in-delfzijl/

11.1.2 Aviation Demand

Having a LH_2 source in the Northern Netherlands would enable greater penetration into the mobility sector for regional airport applications such as in Eelde, which is only 50km away from Delfzijl. Groningen Airport Eelde is the first Hydrogen Valley Airport in Europe. It is well positioned for the use of hydrogen not just geographically, but also through its experience within collaborative hydrogen activities such as HEAVENN and EnableH2. EnableH2 conducted research (undertaken by HyEnergy on behalf of the European Hydrogen Association) to enable development of LH_2 technologies for civil aviation by assessing critical aspects of liquid hydrogen-based propulsion. Having a LH_2 supply from a local producer within the hydrogen valley, would increase the efficiency and cost benefits for direct testing and introduction at Groningen Airport Eelde.

Figure 31. Groningen Airport Eelde – solar & hydrogen plan[112]

Additionally, being a regional airport means flights do not normally travel long distance journeys, which is where hydrogen powered aircraft will enter the zero-emission market up to a predicted 3,000km range. Countries and specific airports nearby, (e.g. Tallinn, Rotterdam, Kirkwall etc.) are all looking to develop their hydrogen infrastructure, meaning outbound flights from Groningen will be able to refuel at their destinations without worry in the upcoming decades. Tallinn Airport in Estonia, was also an EnableH2 partner, and the local region is looking to establish a hydrogen valley, which will supply green hydrogen for fuelling public transport, heavy duty vehicles, rail, shipping, aviation, and other transport modalities[109]. Tallinn airport is only 1,324km by plane from Groningen Airport Eelde. Kirkwall, UK, has been central to the development and testing of the ZeroAvia's hydrogen powered regional aircraft[110] and Rotterdam has plans to become a LH_2 focused, zero-emission aviation hub[111].

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[109] Tallinn Airport to develop new Hydrogen Valley. International Airport Review. Accessed at: https://www.internationalairportreview.com/news/178529/tallinn-airport-to-develop-new-hydrogen-valley/#:~:text=Tallinn%20Airport%2C%20alongside%20partners%2C%20will,'from%20zero%20to%20green'. (2022)
[110] ZeroAvia. ZeroAvia wins two additional UK Government grants to enable clean aviation. Accessed at: https://zeroavia.com/zeroavia-wins-two-additional-uk-government-grants-to-enable-clean-aviation/ (2021)
[111] H2View. Consortium targets liquid hydrogen infrastructure for Dutch airports. Accessed at: https://www.h2-view.com/story/consortium-targets-liquid-hydrogen-infrastructure-for-dutch-airports/2127598.article/ (2025).

Eelde airport has plans to transition all ground operations to zero-emission by 2030 with intentions to establish a multi-fuel filling station, including hydrogen, to service both groundside and airside vehicles.[112] On the groundside, passenger cars, trucks and regional buses will be able to refuel. On the airside, this will serve ground handling equipment, hydrogen drones and hydrogen-powered aircraft in the future. To support these developments, Eelde plans to produce its own green hydrogen using an electrolyser powered by a 21.9MW solar farm[113], however larger hydrogen aircraft will require liquid hydrogen to enable medium-scale journey distances. Establishment, therefore, of liquefaction capacity at Delfzijl could ideally support these local developments. The Hydrogen-Powered Aviation report (CHP and CleanSky2) states that if an average sized regional airport were to switch 10% of their fuel to liquid hydrogen, it would require 5,000 tonnes a year (14tpd). However, initial demand of Eelde will be a fraction of this. Such volumes easily allow LH_2 to be trucked to the airport. To completely replace fuel requirements at the airport will require substantive quantities of hydrogen. The knowledge of handling hydrogen and chemicals in the region would then be leveraged. This will need to be translated into aviation applications via appropriate work practices, codes and standards. For example, new refuelling protocols for multiple fuel types, such as gaseous hydrogen, LH_2 and other fuels like SAF will need to be developed with additional fuel bunkering systems. In Europe the DelHyVEHR project is developing a high-rate LH_2 refuelling station dedicated to maritime, aviation and railroad applications with delivery flowrate exceeding 5t/hr and zero boil-off losses[114].

The Netherlands has six regional airports, along with several other small airfields such as Drachten who have existing interest in hydrogen and SAF. Regional airports will require access to LH_2 to run operations in a net zero economy, thereby presenting opportunities for an appropriately sized development at Delfzijl. According to Dutch aviation statistics, Groningen Airport Eelde had 591 outbound flights, carrying 51854 passengers in 2024[115], which, with a fuel consumption of 3.5-4.5L per passenger per 100km[116] over an average flight distance of 1140km[117], equates to around 4-5tpd of kerosene (5500-7250L/day). Within the International

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[112] At Groningen Airport Eelde Europe's first 'Hydrogen Valley Airport' will be developed, EuroControl. Accessed at: https://www.eurocontrol.int/interview/groningen-airport-eelde-europes-first-hydrogen-valley-airport-will-be-developed

[113] Groningen Airport Eelde becomes the first Hydrogen Valley Airport in Europe. Groningen Airport Eelde. Accessed at: https://www.groningenairport.nl/en/news/groningen-airport-eelde-becomes-the-first-hydrogen-valley-airport-in-europe (2021)

[114] About the project. DelHyVEHR. Accessed at: https://delhyvehr.eu/the-project/ (2024)

[115] Aviation; monthly figures of Dutch airports. StatLine. Accessed at: https://opendata.cbs.nl/#/CBS/en/dataset/37478eng/table?searchKeywords=aviation (2025)

[116] How much fuel per passenger an aircraft is consuming? OpenAirlines. Accessed at: https://blog.openairlines.com/how-much-fuel-per-passenger-an-aircraft-is-consuming (2018)

[117] https://www.eurocontrol.int/sites/default/files/2024-07/eurocontrol-data-snapshot-46-average-flights-eurocontrol-area.pdf

Aviation Transport Association's Net Zero 2050 draft[118], it estimates that 13% of aircraft will be required to use new technology such as electrified or hydrogen powered aircraft. Assuming a conservative 10% is for hydrogen powered aviation due its superior properties to electricity, we can assume that Eelde would have a market of around 0.15-0.25tpd in 2050 for LH_2 – based on today's air traffic, but if returned to pre-covid 19 levels of 88,000 passengers a day, with additional growth, this number could rise significantly, especially with Eelde showing a lot of interest in hydrogen and looking like an early mover in the space. If 50% of the flights were powered by hydrogen of sorts this demand could feasibly exceed 1tpd. Establishing hydrogen powered domestic flights could be easier in the Netherland's regional airports due to congruent legislation as the government is expecting greater penetration of hydrogen into the aviation sector. Greater penetration could be achieved, however, if Airbus, who had 44% of commercial aircraft deliveries in 2024[119], achieve a commanding position in new aircraft sales in the next decade. The company's hydrogen focused approach is likely to influence airports and aircraft manufacturers, to support installation of hydrogen infrastructure and encourage airline operators to pursue this technology.

11.1.3 Maritime Demand

The port of Eemshaven is located 20km North of the Delfzijl chemical cluster with the port of Delfzijl just 3km away. Both of which, as part of Groningen Seaports, have been taking an interest in hydrogen. The port of Eemshaven has experience in importing energy including traditional fuels and LNG. In 2022, the port developed its flagship EemsEnergyTerminal, a floating LNG terminal. In 2025, the project set out plans for a new phase, pending FID, including investigation of the potential to build a hydrogen import terminal and developing a CO_2 transport hub.[120]

Figure 32. Groningen Seaport[120]

[118] IATA. Net Zero 2050: New Aircraft. Accessed at: https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet-new-aircraft-technology/ (2024)
[119] Shaking out the Airbus and Boeing 2024 delivery numbers. Cirum aviation analytics. Accessed at: https://www.cirium.com/thoughtcloud/ascend-consultancy-shaking-out-the-airbus-and-boeing-2024-delivery-numbers/ (2025)
[120] Annual figures: Groningen Seaports is continuing to achieve growth in its ports, Groningen Seaoirts. Accessed at: https://www.groningen-seaports.com/en/nieuws/annual-figures-groningen-seaports-is-continuing-to-achieve-growth-in-its-ports/

Other projects include RWE who announced the Eemshydrogen project, where they will construct an electrolyser running on solar and wind energy to produce green hydrogen on the Eemshavencentrale site. The hydrogen will be transported by pipe to end users like the chemical industry located at the Delfzijl Chemical Cluster and potentially into the hydrogen backbone, enabling it to be stored in underground salt caverns at sites like at nearby Zuitwending. LH_2 at the port of Eemshaven could be used in several applications such as fuelling heavy-duty port based machinery used in loading and unloading goods from cargo ships, as well as a maritime fuel. Such maritime use of LH_2 is being rapidly advanced. Figure 33 shows a render of one of the LH_2 bulk carriers due to be developed by LH2 Shipping following funding from the Norwegian Government[121]. In addition, the EU project NAVHYS is seeking to provide a concept for a below-deck LH_2 storage and fuel system for a 'Service Operation Vessel' that provides maintenance for offshore wind farms[122]. It is envisaged that LH_2 vessels are expected to be capable of journeys of up to 4,000 nautical miles which would enable travel between locations such as the east coast of the US and Egypt (through the Suez Canal), as well as all locations in the EU. This large radius is well within the distance of routes commonly accommodated by the port of Eemshaven, and opens the opportunity for economic hydrogen powered trade growth by establishing shipping links to hydrogen regions across the world[123]. Thereby enabling a fairly seamless transition from polluting large diesel engines to LH_2 power. Similarly to the aviation sector, longer journeys may involve an alternative zero emission fuel many of which are currently being trialled and developed.

Figure 33. LH2 Shipping's Rendering of Their LH_2 Shipping Vessel[121]

Eemshaven is also a ferry terminal with direct links to Kristiansand in Norway, who have already deployed LH_2 passenger ferries. Whilst this ferry route does not currently run due to the financial difficulties of the operator, Kristiansand to Emden, Germany does. Therefore, establishing LH_2

[121] Norwegian firm wins state cash to build 'world's first' liquid-hydrogen-powered bulk carrier ships, Hydrogen Insight. Accessed at: https://www.hydrogeninsight.com/transport/norwegian-firm-wins-state-cash-to-build-worlds-first-liquid-hydrogen-powered-bulk-carrier-ships/2-1-1841230

[122] ArianeGroup's NAVHYS project: liquid hydrogen for maritime transport. Ariane Group. Accessed at: https://ariane.group/en/news/17534/ (2025)

[123] EEMSHAVEN, NETHERLANDS (NLEEM). Vessel Finder. Accessed at: https://www.vesselfinder.com/ports/NLEEM001 (2023)

storage and refuelling infrastructure in northern Netherlands and German ports, presents an opportunity to decarbonise North Sea travel. Additionally, zero emission fuel bunkering infrastructure would facilitate fossil powered ferries making use of decarbonised cold ironing services, a process where the port provides shoreside power to a stationary ship while its main and auxiliary engines are turned off. Further ferry connections, such as between Borkum and Eemshaven, as well as between the Wadden Islands archipelago ports, could also make best use such LH_2 infrastructure. This opportunity could be bolstered by regional funding mechanisms, such as the Wadden Fund, which specifically supports sustainable shipping and connected activities in the Wadden Sea.

With multiple LH_2 application possibilities within Groningen Seaports and neighbouring ports, who also have their own activities around initialising hydrogen production, there is significant potential for maritime LH_2 demand around Delfzijl. When it comes to ferries, Groningen Seaports and Borkum could have a large daily demand for LH_2 powered vessels during peak season, as they have multiple departures and arrivals per day. An exact figure is difficult to calculate due to changes in timetables throughout the year, differences in vessel types and the unknown differences between diesel powered fuel consumption and LH_2 powered vessel fuel consumption. However, this daily demand is estimated to be between 5tpd and 10tpd in peak ferry season, as there are nearly 1000km of journeys per day from the locations mentioned with fuel consumption estimated between 20l/km and 40l/km of diesel. The location of a LH_2 facility at Delfzijl and its use of proximal offshore wind resources would minimise production and distribution costs to these demands enhancing the region's attractiveness for such additional energy/hydrogen investments.

11.1.4 Inland Waterways Demand

Delfzijl has a large network of inland waterways directly connected to the chemical cluster and port. In 2022, the Port of Delfzijl handled 5.0 million tonnes cargo from inland waterway vessels[124], showcasing significant scale. As mentioned in the maritime applications section of this report, inland barges are a viable and trusted method of transporting LH_2 across countries thereby also representing a potential additional distribution method to road-based solutions. With barges already demonstrating gaseous hydrogen powertrains in the Netherlands, expansion to liquid for either refuelling requirements or greater performance characteristics is expected in certain areas. The Antonie, operated by Lenten Scheepvaart, moves salt from Delfzijl to Rotterdam on behalf of Nobian. It utilizes 1,200kg of gaseous hydrogen to power its fuel cells each round trip. LH_2 could provide a number of benefits including increased range, reduced refuelling instances and larger payloads.

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[124] Market Observation Annual Report 2023. CCNR. Accessed at: https://inland-navigation-market.org/chapitre/5-inland-waterway-cargo-handling-in-ports/?lang=en (2023)

11.1.5 Mobility Demand via HRS Network

In the Netherlands, there are 19 HRSs [125], including one in Groningen and one in Assen. There are 17 locations within a 150km radius of Delfzijl, with many just outside that zone, that will be required to install an HRS under AFIR, including 6 locations on German soil. However, with AFIR coming into effect by 2030, several more locations will have to install HRS' in major urban nodes such as Groningen, Zwolle, Apeldoorn, and Emmen along with various points along the Baltic Sea Ten-T corridor, which spans into Amsterdam. These stations will be required to be capable of delivering at least 1tpd of hydrogen refuelling capacity and will thus require even greater storage for fuel security.

Figure 34. Netherlands Potential HRS Networks

The EU average for motorways with more than 4-lanes has an average flow of HGVs greater than 9,100 vehicles per day. On motorways with 4-lanes or less, the average flow of HGVs is just over 4,300 vehicles per day[126]. However, in the Netherlands, these averages are over 11,000 and 8,000 respectively. This suggests that AFIR complaint locations that intersect or lie near motorways, specifically on the Ten-T corridor or are located at a key urban node will require greater fuel storage due to greater use. Five locations outlined in Figure 34 will fall under this this criterion, creating a total potential demand of 7.5-10tpd across the five HRSs (1.5-2tpd each). This could increase given that some heavy-duty vehicle OEMs are considering on board LH_2 storage as a model variant. Such variants would be more likely to be used on long distance trucking routes i.e. those covered by the Ten-T corridors and the core road network.

[125] Hydrogen vehicle registrations are flatlining across most of Europe – with hundreds more filling stations on the way. Hydrogen Insight. Accessed at: https://www.hydrogeninsight.com/transport/exclusive-hydrogen-vehicle-registrations-are-flatlining-across-most-of-europe-with-hundreds-more-filling-stations-on-the-way/2-1-1592413 (2023)
[126] 2023 Pan European Road Network Performance Report. CEDR. Accessed at: https://horizoneuropencpportal.eu/sites/default/files/2024-12/cedr-2023-pan-european-road-network-performance-report-2024.pdf (2024)

Therefore, these high demand HRS locations would benefit from LH_2 storage as it offers significant advantages over gaseous high-pressure alternatives. We have discussed how LH_2's higher volumetric density enables more effective storage and transportation when compared to many compressed gas options. Additionally, cryogenic pumps play a crucial role in this system. These pumps can efficiently convert LH_2 into high-pressure gas at 350 bar and 700 bar, meeting the demands of modern hydrogen vehicles, at a fraction of the footprint required for an equivalent gaseous system. They are also a proven, robust technology having been used in US industrial applications for many years. This capability aligns with AFIR's goals to promote the widespread adoption of hydrogen fuel, ensuring that refuelling infrastructure is fit for purpose and capable of handling the high volumes and pressures required by contemporary hydrogen fuel cell vehicles.

LH_2 can also be more efficient delivery mechanism for hydrogen to these HRSs. Current hydrogen tube trailers have capacities up to 1.4 tonnes, whereas LH_2 tankers have maximum capacities of around 3.5-3.9 tonnes, reducing the number of trips necessary to service each HRS. Projections show that hydrogen heavy duty vehicles will play a crucial role in the decarbonisation of heavy-duty transport. It is clear that a strong HRS network is going to be key to support zero emission freight distribution, either in or through the Netherlands each year. In 2021 this was 44,981 million tonne kilometres[127].

In addition to HRSs, Groningen and the surrounding regions, have an extensive bus network operated by key private and public transport companies such as QBuzz and Arriva, who both operate and own hydrogen buses in the Netherlands. In 2023, there were 200 million passenger kilometres taken by bus, tram or metro in the Groningen region[128]. Bus operators running hydrogen buses, will be able to utilise LH_2 as a storage method enabling the same benefits seen for AFIR stations. With fuel cell buses gaining in popularity, the market is expanding, and depots will need the means of accessing greater quantities of energy without compromising space. Underground LH_2 tanks have been trialled in the US, these, along with the potential to submerge cryogenic pumps inside the LH_2 storage tank – similar to some tanks deployed in LNG service – offer future optimisations.

11.1.6 Demand Summary

As discussed above, over greater distances, it can be more effective to distribute LH_2 compared to gaseous hydrogen in tube trailers. To access these LH_2 benefits there is a need to deploy a liquefaction facility or import terminal with associated local storage in the northern Netherlands. The existing liquefaction facilities in locations such as Rotterdam already have demand and off-

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[127] Amount of freight transported by road in the Netherlands from 2007 to 2021. Statista Accessed at: https://www.statista.com/statistics/435431/netherlands-tonne-kilometres-of-freight-transported-by-road/ (2023)

[128] Total transport performance in the Netherlands; modes of travel and regions. Statistics Netherlands. Accessed at: https://www.cbs.nl/en-gb/figures/detail/84687ENG?q=Groningen (2024)

takers of their supply. New or expanded facilities are expected to quickly to become sold out as local applications ramp up. This also applies to the liquid import facilities in Amsterdam, where offtake has been dedicated to hydrogen use in steel manufacturing.

Figure 35. Map of potential liquid hydrogen supply demand areas

As hydrogen energy applications become more mature, technologically ready and commercially available, demand is projected to exponentially increase, requiring a wider network of production sites. Figure 35 shows a map of the locations of potential off takers for LH_2 inside a radius of 150km of Delfzijl, along with 150km boundaries for existing (blue) & planned (green) liquefaction sites and planned (green) LH_2 import locations. Key HRS sites set be developed as part of the AFIR locations along the Ten-T/urban node network are shown along with regional ports and airports.

Based on the estimated possible demand from the applications mentioned above, a suitable sized facility would be a 30tpd liquefier. 30tpd facilities are a typical size being deployed by industry today. It highlights geographic gaps and the arising opportunity for a localised supply for the northern Netherlands region. Such a facility would support the positioning of Delfzijl and the northern Netherlands to become one of Europe's prominent LH_2 energy hubs.

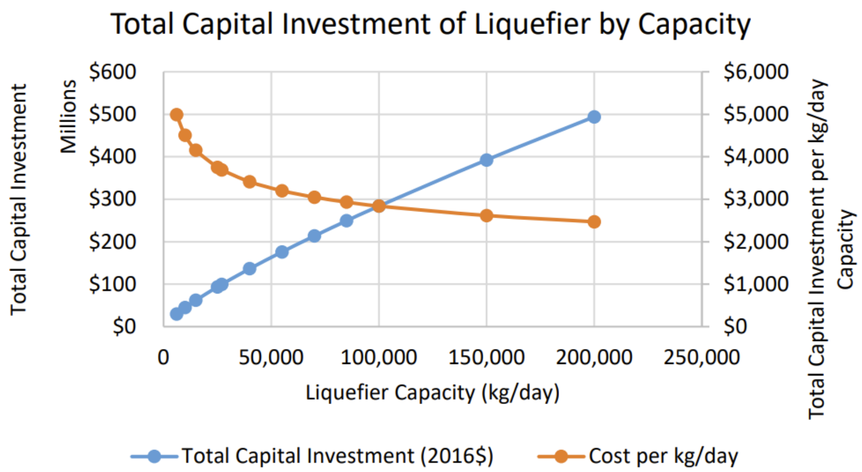
11.2 Northern Netherlands Liquefier cost analysis

The previous sections have highlighted how well suited the northern Netherlands region is for establishing a hydrogen liquefaction plant. This section presents a cost analysis of constructing and operating a hydrogen liquefaction plant in Delfzijl.

11.2.1 Liquefaction

The US DoE's assessment of liquefaction was summarised in their 2019 report "Current Status of Hydrogen Liquefaction Costs". Costs for a c.30tpd liquefaction facility, corrected for inflation and location, are expected to be just over €125 million[129].

Given the US's focus on LH_2 it is no surprise the DoE wishes to scale up production driving up capacity per plant significantly. Once initial plants are built it expect a rapid reduction in cost over the next decades. However, as we see from today's market liquefaction requires demand and, today, there is probably more uncertainty over the LH_2 focused hydrogen applications than there was in 2019. Energy costs and hydrogen market pricing remain volatile and such investments require solid market forecasts with contractual price/cost certainty. In Europe, scaling to today's 30tpd industry norm will, in the short to medium term, be sufficient to meet market demand.



11.2.2 Storage

To provide a level of value chain supply security for LH_2 end users during ramp down periods, service intervals or technical breakdowns, a minimum storage capacity of c.4 days will likely be required equating to a vessel with 120 tonnes storage capacity. As the tank will be in constant

Figure 36. US DoE LH_2 scale up costs[129]

[129] Current Status of Hydrogen Liquefaction Costs. Department of Energy. Accessed at: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/19001_hydrogen_liquefaction_costs.pdf?Status=Master (2019)

use, boil-off will be low. Storage of 120 tonnes will likely occur using one or two large spherical tanks.

Whilst supply of 30tpd is not likely to be required from the start-up of the plant, building the full anticipated required storage is likely to have future operational benefits. Large LH_2 storage requires appropriate management of activities taking place in its vicinity. Therefore, if land is at a premium, it is likely to be more cost and operationally effective to build the full plant storage during initial construction instead of deferring it until demand grows. However, as the value chain develops, LH_2 storage across the value chain will also develop, with end users such as airports and HRSs requiring local storage increase their own security of supply, resulting in higher storage volumes across the supply chain.

11.2.3 Distribution

The CAPEX of a LH_2 tanker must be factored in when considering distribution methods and business models. A 4000kg trailer is estimated to cost between €750,000-1,250,000 in 2030, but there are projects working on developing new materials for cryogenic storage with the aim of bringing costs down to €100/kg, reducing costs by more than 50%. The number of tankers required is dependent on the off-take requirement and location of these off-takers, as this will affect the number of deliveries and whether deliveries will be conducted from point-to-point or 'milkman' style. Redundancy will be key to ensure deliveries are made on time even if a tanker is out of operation.

11.2.4 Analysis Assumptions

Within this analysis, production, storage and distribution costs have been assessed. Expected, low and high projects are made.

The analysis made has been based on the following assumptions:

- The facility is sized to deliver 30tpd of liquified hydrogen
- It is assumed to operate an average of 358 days of the year
- The facility cost itself is based on the DoE report, the 2016 figures provided have been adjusted for location and inflation
    - A high and low scenario of ±10% is used for the facility cost
- Storage costs were based off the JRC technical report of €150-300/kg[20], with a capacity of 120,000kg, which is four days of LH_2 storage at a demand of 30tpd
    - The mid-point is used for the expected scenario (225)
    - The upper (300) and lower (150) bands being used for the high and low scenarios
- 10 tankers are assumed to exit product from the plant
- The assumed average maintenance cost is 4% of total capex (facility + storage + trailers)
    - A high and low scenario of ±1% is used
- The energy consumption of the plant is assumed at 8kWh/kg of LH_2

    - The low scenario assumes 6kWh/kg and the high assumes 10kWh – all of which are efficiency improvements from current models
- Energy produced by fixed offshore wind turbines is expected cost between €35/MWh and €60/MWh in the Netherlands[130]
    - the mid-point is used in the expected scenario (47.5)
    - the upper (60) and lower (35) is used for the low and high scenarios

Figure 37 shows a simple cost analysis of operating a 30tpd hydrogen liquefaction facility, using renewable energy and green hydrogen for the liquefaction process. These scenarios assume a stable operation at the capacity of the plant with minimal down time. Reductions in production rate, frequent starting and stopping of the process and energy supply fluctuations will result in significant cost and operational (downtime) penalties. As a 30tpd liquefier is rapidly becoming an industry standard there is potential to reduce engineering costs for repeat plant designs.

	Expected	**Low**	**High**
	CAPEX (€ Millions)		
Facility Cost	127.00	114.30	139.70
Storage Cost	27.00	18.00	36.00
Tankers (10 off)	10.00	7.50	12.50
Total	**164.00**	**139.80**	**188.20**
	OPEX (€ Millions/year)		
Maintenance	6.56	4.19	9.41
Energy Cost	4.08	2.26	6.44
Total	**10.64**	**6.45**	**15.85**
	Liquefaction Additional Cost (€/kgH2)		
Total Cost of Liquefaction	2.20	1.55	3.05
	Distribution via road tankers (€/kgH2/km)		
LH_2 Tankers	0.0050	0.0025	0.0075

Figure 37. Costs associated with building and operating a 30tpd liquefaction plant

[130] SETIS - SET Plan information system. European Commission. Accessed at: https://setis.ec.europa.eu/implementing-actions/wind-energy_en#:~:text=Targets%20and%20objectives&text=reach%20an%20average%20levelised%20cost,2030%20for%20floating%20offshore%20wind. (2023)

11.3 Hydrogen Supply Pathways

This section explores some of the potential international pathways to enable the large-scale deployment of LH_2 in the northern Netherlands, with a focus on infrastructure investment, logistical challenges, and cost competitiveness.

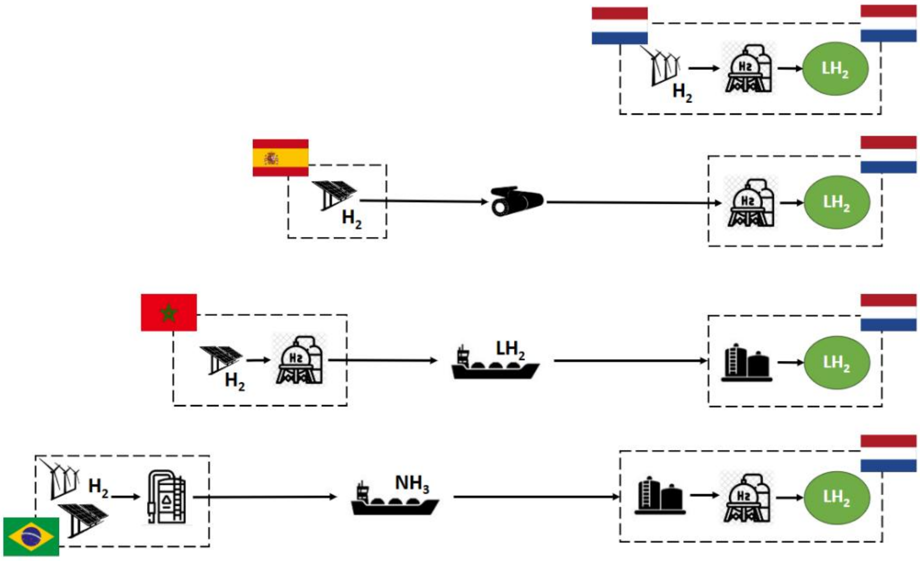


Figure 38. Explored hydrogen supply pathways

Hydrogen imports are increasingly seen as a viable option to supplement or displace domestic production in the Netherlands, particularly as countries with higher renewable energy capacity factors. In this report we consider three such countries Spain, Morocco[35], and Brazil[131] who are each projected to produce hydrogen at lower costs by 2030. These countries not only benefit from superior solar and wind resources, but have improving grid infrastructure and strong government backing for green hydrogen production. International connections between these renewable energy rich countries are currently being explored across Europe with initiatives such as H2EART[132], which aims to develop a cross-border hydrogen valley and bolster energy security through imports of clean and cheaper hydrogen from Brazil for demand centres in the Netherlands and Germany.

[131] Green Hydrogen: an opportunity to create sustainable wealth in Brazil and the world. Accessed at: https://www.mckinsey.com/br/en/our-insights/hidrogenio-verde-uma-oportunidade-de-geracao-de-riqueza-com-sustentabilidade-para-o-brasil-e-o-mundo (2021)
[132] H2EART: Building a Cross-Border Hydrogen Valley. Th!nk East NL. Accessed at: https://thinkeast.nl/en/news/h2-eart-building-a-cross-border-hydrogen-valley (2025)

The method of transfer of the hydrogen molecule varies with distance to be travelled and availability of infrastructure. The options considered here include transfer by pipeline, ammonia and LH_2 itself.

11.3.1 Import Infrastructure

There is currently no existing infrastructure in the northern Netherlands capable of supporting carbon free hydrogen carrier imports at scale. This means new import terminals will need to be constructed alongside any required liquefaction facilities. Such costs must be added to the LH_2 delivered cost. Terminals, such as the ones mentioned, have similar infrastructure needs to LNG terminals, which were assessed in a Global Energy Report monitor, using real world examples, as taking between 2.5 years to 6 years from FID to completion, depending on size[133]. LH_2 terminals, and liquefiers themselves, sit within this timeframe, even though there is a lack of scaled up existing terminals to draw experience from.

11.3.2 Comparative Pathways

Based on the base LCOH values and added infrastructure costs, the following insights emerge and are showcased within Figure 39, splitting each cost up to enable understanding of the hydrogen value chain[134]:

Location	Distribution Method	H_2 Production Cost(€/kg)	H_2 Distribution Cost(€/kg)	Liquefaction Cost (€/kg)	Total Cost of Liquid Hydrogen (€/kg)
Netherlands	Onsite production	3.25 - 4.55	[redacted]	1.55-3.05	4.80 - 7.60
Spain	Pipeline	3.00 - 3.20	0.25 - 0.50	1.55-3.05	4.80 - 6.75
Morocco	LH2 Ships	2.50 - 2.75	2.25 - 2.50	[redacted]	4.75 - 5.25
Brazil	NH3 Ships	1.60 - 2.30	2.00 - 2.25	1.55-3.05	5.15 - 7.60

Figure 39. Comparison of Hydrogen Costs Across the Value Chain from Production to Liquefaction.

Production costs based on HyEnergy calculations (Netherlands), and previous analyses from Aurora[160] (Spain), The Oxford Institute for Energy Studies[161] (Morocco), and McKinsey[151] (Brazil). Distribution costs based on the IEAs Global Hydrogen Review 2022 and include costs for conversion, export and import terminals (including storage), and shipping vessels. Liquefaction costs from HyEnergy analysis described on page 64 of this report.

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133 How Long Does it Take to Build an LNG Export Terminal in the United States. Global Energy Monitor. Accessed at: https://globalenergymonitor.org/wp-content/uploads/2022/04/GEM-Briefing-LNG-Terminal-Development-Timelines.pdf (2022)

134 Assessment of hydrogen delivery options. European Commission. Accessed at: https://joint-research-centre.ec.europa.eu/document/download/5cdbd6f7-7ab4-447b-be0a-dde0a25198ab_en#:~:text=In%20the%20case%20of%20hydrogen%20delivered%20by,cost%2C%20making%20this%20option%20even%20more%20competitive.&text=For%20short%20distances%20(up%20to%203%2C000%20km)%2C,option%2C%20particularly%20in%20the%20case%20of%20pipelines (2021)

Dutch renewable hydrogen produced from electrolysers clustered along the coast near Eemshaven/Delfzijl is assumed to be piped directly the liquefaction plant by grid connection. Given the variable cost of power, gaseous hydrogen costs of between €3.25 and 4.55/kg are calculated for the feedstock to the liquefier.

Figure 40. Illustration of LH_2 ship & EcoLog Import terminal at Port of Amsterdam[136]

Spain via pipeline currently offers the cheapest supplied LCOH by 2030 (€3.25–3.70/kg), with base production costs estimated to be around €3.00-3.20/kg[135], with distribution between €0.25-0.50. However, to convert this gas-phase hydrogen to LH_2, a liquefaction facility would need to be built in the Netherlands, adding €1.55–3.05/kg, for a total LCOH of €4.80–6.75kg. To support this pathway Spain has a large export potential due to its high solar capacity factor, enabling cheaper hydrogen production. Spain is also seeking to become a gateway to African hydrogen production via its position as a major player in the H2Med project, which aims to run pipelines from North East Africa through Spain connecting to other European countries to enable onward hydrogen distribution throughout Europe.[136]

For this analysis Morocco is assumed to export hydrogen via LH_2 shipping, which avoids the need for a liquefaction facility at the import point. It therefore has a LCOH of €4.75-5.25/kg[137], a competitive option. However, the infrastructure investment required to be able to onboard this liquid hydrogen will be significant with storage being a large factor. An entirely new liquid hydrogen import terminal would be required, of which there are none currently in Europe, so the experience and knowhow is very limited, potentially making it a risk. Furthermore, someone in the value chain

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[135] Renewable hydrogen imports could compete with EU production by 2030. Aurora Energy Research. Accessed at: https://auroraer.com/resources/aurora-insights/articles/renewable-hydrogen-imports-could-compete-with-eu-production-by-2030 (2023)

[136] Gen2 Energy signs collaboration agreement with TATA Steel and ECOLOG for import of green hydrogen to The Netherlands, Gen2Energy. Accessed at: https://gen2energy.com/gen2-energy-signs-collaboration-agreement-with-tata-steel-and-ecolog-for-import-of-green-hydrogen-to-the-netherlands/

[137] Green Hydrogen Imports into Europe: An Assessment of Potential Sources. The Oxford Institute For Energy Studies. Accessed at: https://www.oxfordenergy.org/wpcms/wp-content/uploads/2024/04/ET32-Green-Hydrogen-Imports-into-Europe-An-Assessment-of-Potential-Sources.pdf (2024)

will have to incur the cost of the developing/buying and operating the LH_2 shipping tanker, which if built to size like the Suiso Frontier, could cost over $350 million[138]. If the same level of storage and trailers are still required from imports as the liquefaction facility, using the same parameters, the additional cost could add €0.28-0.69/kg making the total €4.78-5.69/kg. Morocco has several MoUs with European entities looking to mainly export hydrogen molecules, as LOHC's, this includes the MoU between LONDON (ICIS)–CWP Global and Hydrogenious LOHC Technologies, who are investigating development of LOHC transport corridors between Morocco and Europe. Whilst this does not include LH_2, the development of transport corridors highlights Morocco's intentions to export hydrogen to Europe, and with the growing interest of LH_2 across Europe, combined with Morocco's cheap production and proximal location, LH_2 should be seen as a prime export alternative from North West Africa.

Brazil, using shipped ammonia, offers a potential lower production cost at €1.60–2.30/kg by taking advantage of extremely cheap renewable electricity generation in on-grid regions of North-East and South-East of Brazil, but the need to reconvert ammonia to hydrogen and build a LH_2 liquefaction facility adds significant cost, pushing the total LCOH from Brazil for LH_2 to €5.15-7.60/kg. This results in a potentially expensive looking pathway for meeting LH_2 demand via NH_3 imports, despite the attractiveness of Brazil's renewable capacity. However, the variation in the investment costs coupled with the scale being considered by Brazilian exporters suggest costs at the lower end of this range. Brazil will therefore be a viable option for hydrogen molecule export. A key project between Vale and Green Energy Park in Brazil was awarded the EU's Global Gateway Status in 2025[139]. The Global Gateway is a European Union initiative that aims to commit up to €300 billion in global investments between 2021 and 2027. Focusing on sustainable, high-quality investment projects in sectors such as digital, climate and energy, transport, health, education and research. These projects aim to strengthen strategic partnerships and promote the integration of EU value chains with strategic partner countries. Figure 39 outlines the LCOH using the various hydrogen supply routes and carriers, assuming no added profit margin.

11.3.3 Final distribution of LH_2 to customers

Distribution of LH_2 by trailer is expected to be €0.005/kg per km in 2030 (cost between €0.0025-0.0075). To estimate total yearly delivery costs, the end users need to be identified with demand

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[138] Welcoming the Revolutionary "Suiso Frontier" the World's First Liquefied Hydrogen Vessel at Sultan Qaboos Port. Oman Hydrogen Centre https://www.ohc.om/welcoming-the-revolutionary-suiso-frontier-the-worlds-first-liquefied-hydrogen-vessel-at-sultan-qaboos-port/#:~:text=The%20Suiso%20Frontier%20transports%20substantial,is%20approximately%20USD%20359%20million.

[139] Partnership between Vale and Green Energy Park in Brazil receives Global Gateway flagship status by the European Union. Vale. Accessed at: https://vale.com/w/partnership-between-vale-and-green-energy-park-in-brazil-receives-global-gateway-flagship-status-by-the-european-union (2025)

specified, as trailer capacities and distances drastically affect total costs over an extended period. With several possible off takers identified, such as Groningen Airport Eelde, Port of Eemshaven, Port of Delfzijl (plus their ferry port connections) and a varied HRS network developed as part of the AFI Regulation, and without knowledge of the optimised distribution methodology, it would be inaccurate to speculate on total costs per annum. Based on the cost projections given a 100km round trip journey, carrying 3,500kg of hydrogen would be expected to cost around €1,750 per journey and, assuming all the liquefied hydrogen travelled an equivalent distance, over €15,000 per day (equating to €5m+ year). This translates to ~€0.5/kg of hydrogen delivered.

11.3.4 LH_2 versus GH2 HRS

HRSs utilising LH_2 storage employ distinct designs that leverage more cost-effective and efficient technologies. Specifically, LH_2 HRSs can incorporate cryogenic pumps, which offer higher efficiency and lower CAPEX compared to the gaseous compressors typically found in GH2 HRSs. Furthermore, gaseous compressors generally have a larger physical footprint and are noisier, impacting the overall station design and land requirements. A report conducted by the National Renewable Energy Laboratory (NREL) analysed the Levelised Cost of Dispensed Hydrogen for Heavy-Duty Vehicles in the USA in 2022, which acts as the financial basis for the following comparison[140]. Figure 41 illustrates a typical simplified configuration for both GH2 and LH_2 HRS, highlighting the fundamental differences in their delivery and storage mechanisms.

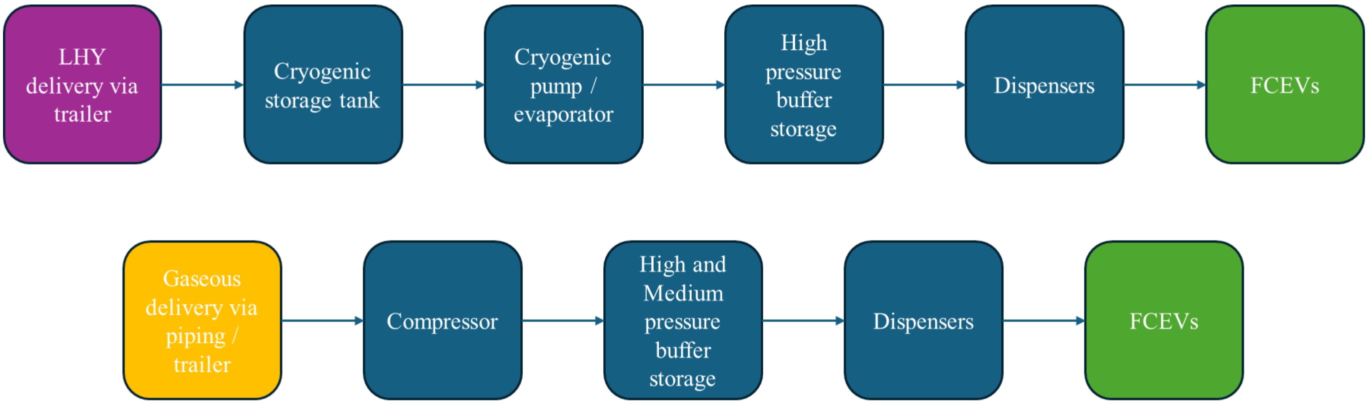

Figure 41. Simplified LH_2 and GH2 HRS configuration[140]

As depicted in Figure 41, the core configurations of LH_2 and GH2 HRSs exhibit notable similarities with key distinctions in the initial stages of hydrogen handling. A primary advantage of LH_2 delivery, typically via trailer, is its direct transfer into a cryogenic storage tank. Subsequently, a cryogenic pump/evaporator is used to convert the LH_2 to a high-pressure gaseous state, which

[140] Levelized Cost of Dispensed Hydrogen for Heavy-Duty Vehicles. NREL Accessed at: https://docs.nrel.gov/docs/fy24osti/88818.pdf (2022)

then proceeds to high-pressure buffer storage before being dispensed to FCEVs. In contrast, GH2 delivery, whether via piping or trailer, first enters a compressor. This compression step is crucial as gaseous delivery often results in lower pressure outputs, necessitating compression to achieve the high pressures required for high and medium pressure buffer storage and subsequent dispensing to FCEVs. This compression requirement is a significant factor contributing to the increased complexity and cost of a GH2 HRS, which are showcased in Figure 42.

Total Estimated Costs (nameplate dispensing capacity)	On-Site GH_2 Station (700 bar dispensing) (2022$)	LH_2 Station (700 bar dispensing) (2022$)
Capital Cost (2022$) (2TPD)	$11.0 million ($5,500/kg/day	$5.92 million ($2,960/kg/day)
Capital Cost (2022$) (4TPD)	$20.7 million ($5,170/kg/day)	$10.9 million ($2,730/kg/day)

Figure 42. Estimated costs of Gaseous and Liquid HRS'[140]

Figure 42 provides a comprehensive cost comparison between GH_2 and LH_2 HRS for nameplate dispensing capacities of 2tpd and 4tpd, with all costs presented in 2022 US dollars. As depicted, an LH_2 station demonstrates a significantly lower overall capital cost compared to its gaseous counterpart. For a 2tpd station, an On-Site GH2 Station has an estimated capital cost of $11.0 million, whereas an LH_2 Station is nearly half the cost at $5.92 million. This cost advantage is maintained, and indeed proportionally similar, even with increased scaling to 4tpd, where GH2 costs $20.7 million and LH_2 costs $10.9 million. This substantial cost difference, approximately 50%, is primarily attributable to the difference in required compression equipment an LH_2 HRS. These specific costs are broken down in greater detail in figure 43.

Components	On-Site GH_2 Station (700 bar dispensing) (4TPD)	LH_2 Station (700 bar dispensing) (4TPD)
Compressors and Pumps	8 Total Compressors	4 LH_2 pumps
	Energy: 5.5 kWh/kg	Energy: 0.54 kWh/kg
	CAPEX: $6.96 million	CAPEX: $5.18 million
Storage	401kg cascade storage	10,720kg cryogenic storage tank
	3,100kg low-pressure storage	241 cascade storage
	CAPEX: $8.36 million	CAPEX: $1.91 million
Dispenser	2 dispensers	2 dispensers
	CAPEX $0.37 million	CAPEX $0.37 million
Refrigeration and Heat Exchanger	2 condensing/heat exchange units	2 heat exchangers
	14.5-tonne capacity each	1 evaporator
	Energy: 0.09 kWh/kg	CAPEX: $1.41 million
	CAPEX: $0.57 million	
Electrical, Controls, and Other	BoP and electrical equipment	Bop and electrical equipment
	CAPEX: $0.56 million	CAPEX: $0.27 million
Indirect Capital Costs	CAPEX: $3.87 million	CAPEX: $2.04 million

Figure 43. Component breakdown of different HRS types[140]

Figure 43 provides a detailed component breakdown for 4tpd stations. The most impactful difference lies in Compressors and Pumps: GH2 stations require 8 compressors for this quantity of hydrogen. ($6.96 million CAPEX, 5.5 kWh/kg energy) while LH_2 stations use only 4 LH_2 pumps ($5.18 million CAPEX, 0.54 kWh/kg energy), demonstrating nearly tenfold better energy efficiency for LH_2 pumping. Storage costs are also drastically lower for LH_2 ($1.91 million for 10,720 kg cryogenic tank) compared to GH2 ($8.36 million for 401 kg cascade and 3,100 kg low-pressure storage), reflecting LH_2's superior volumetric energy density.

Whilst HRSs in Europe are not set to be as large as the comparison made above in the US, due to the network of gaseous hydrogen production sites and set distance between future HRS' laid in the AFIR legislation being much closer in proximity, LH_2 storage and pumping technology will likely lead to upfront investment savings due to lower CAPEX - including at smaller capacities.

11.3.5 Funding

Despite the large start-up costs and expensive operating, fuel and energy costs, a liquefaction facility in Delfzijl could be eligible for EU and national funding to help cover all or partial cost of the capex. Only larger funding mechanisms will impact such projects. Some potential alternatives are examined below.As an example, the IPCEI Hy2Use scheme, which distributed €5.2bn across 13 member states in 39 different projects for hydrogen infrastructure and hydrogen applications projects[141]. The scheme aims to bridge the funding gap in projects, where investment is required. Whilst this scheme has had three waves of applications, additional applications would be anticipated as the EU's attempts to realise the hydrogen and decarbonisation targets. Whilst the first iteration of this funding mechanism has proven difficult to implement it can be versatile, aiming to invest in high TRL level technologies and the whole hydrogen value chain – which could include LH_2 infrastructure deployment.

[141] State Aid: Commission approves up to €5.2 billion of public support by thirteen Member States for the second Important Project of Common European Interest in the hydrogen value chain. European Commission. Accessed at: https://ec.europa.eu/commission/presscorner/detail/en/ip_22_5676 (2022)

Another large funding scheme is the EU's Innovation fund. The IF24 call had €2.4 billion available for Net-Zero technologies [142]. This report has showcased that LH_2 can decarbonise hard-to-abate sectors, and various modes of transport including aviation and maritime. Whilst LH_2 production is not a new concept, if the energy efficiency is going to be increased or the technology scaled, novel designs the innovative concepts discussed in this report could create more cost-effective solutions. The innovation fund aims to derisk such projects.

Figure 44. Hydrogen infrastructure & industrial application companies [144]

Funding could also be accessed through SAF routes as airports look to increase their use in current aircraft models to start decarbonisation and need suppliers to develop these fuels. Partnerships with SAF producers, like the SkyNRG facility in Delfzijl, could unlock this funding potential through integrating LH_2 into, and alongside, SAF production value chains. SAF requires sustainable hydrogen in its production process and, therefore, LH_2 can enable scale up and continuity of supply from renewable sources. Simultaneously aligning/mixing growth in both the SAF and LH_2 supply chains will enhance aviation sustainable fuel supplies and project financial security. It will also allow airports to support aircraft OEMs in their LH_2 developments, whilst enabling short/medium term SAF use to enable rapid decarbonisation. As an example, one four-year SAF incentive programme, committed €15 million for SAF promotion (2022-2024) via supporting €500/t of SAF and €1,000/t of synthetic fuels[143]. Capital and operational support models are being considered by the EU and national governments.[144]

[142] https://climate.ec.europa.eu/eu-action/eu-funding-climate-action/innovation-fund/calls-proposals_en
[143] Sustainable Aviation Fuels Financial Support/Incentives Tracker of European Airports. ACI Europe. Accessed at: https://alternative-fuels-observatory.ec.europa.eu/system/files/documents/2024-11/Airport%20SAF%20Initiatives.pdf
[144] IPCEI hydrogen: with Hy2Use, Europe unlocks an additional 5 billion, H2mobile. Accessed at: https://www.h2-mobile.fr/actus/ipcei-hydrogene-hy2use-europe-debloque-5-milliards-supplementaires/

12 Conclusions

This report has demonstrated that LH_2 holds significant potential to decarbonise several challenging transportation sectors, including maritime and aviation, while also enabling large-scale renewable hydrogen storage and intra-regional renewable energy transfer. As a net-zero fuel, LH_2 can play a crucial role in global decarbonisation efforts. However, due to its energy-intensive production, cryogenic storage requirements and higher capital costs, supply chain efficiency improvements would increase its market penetration and provide a demand basis for scaling up, in both size and number of facilities, to enable it to become a major driver of change. This would enhance its competitiveness against alternative energy vectors, such as ammonia and e-methanol for inter-regional energy transfer. Direct vehicle applications for LH_2 are gaining market traction which, providing reliable supply chain availability matches demand, will enhance the technology attractiveness. Longer term migration of technology, particularly from new developments in space and aviation, are likely to lower costs and offer wider application benefits alongside increased distribution and refuelling efficiencies and energy import opportunities.

To support the adoption of LH_2 regional energy transfers, beyond the need to scale liquefaction technologies, new import terminals and larger LH_2 shipping tankers are needed. These will require public financial support and suitable regulatory measures to foster innovation and the adoption of LH_2 as an energy transfer technology of choice. Use of this market opportunity along with interconnection of supply chains for other green fuels or energy transfer vectors, i.e. SAF, will enable the development and deployment of scaled liquefaction supply chains.

Deployment of LH_2 in HRSs offers increased supply security, smaller footprints, reduced noise levels and lower capital costs per station. As heavy-duty vehicle numbers and AFIR HRSs increase LH_2 supply options will offer competitive alternatives to gaseous options. Although the option to have regularly spaced LH_2 HRSs was removed from AFR legislation, the opportunity exists to revisit this policy in future to provide suitable incentives. Transition of onboard LH_2 storage systems in trucks thereby leveraging new composite storage solutions developed for aviation will also drive demand.

Specifically, in the northern Netherlands, this report has identified several potential off-takers for LH_2 across multiple sectors, including the regional airport at Eelde, ports such as Eemshaven, Delfzijl, and Borkum, and an expanding HRS network along TEN-T corridors and urban nodes. Current and near term supply of LH_2 in the Netherlands, even including developments in Rotterdam and Amsterdam, will be insufficient to meet projected demand.

Therefore, the market potential for LH_2 is substantial. Establishing a liquefaction facility in the Delfzijl region is logical due to its existing hydrogen experience, renewable energy potential, and numerous off-takers. The cost analysis indicates that, in today's market, regional LH_2 production can be profitable, however, it is heavily influenced by the cost of energy and hydrogen. Proximity to the North Sea and the Dutch coast, together with interlinkage to the Hydrogen Backbone and new pipeline investments make the location attractive in hydrogen availability terms, leading to an attractive LCOH of green hydrogen. When combined with efficient, and scaled, liquefaction and associated LH_2 technologies the analysis suggests there is a commercial case for making such investments. If other neighbouring regions consider similar investments this could impact the attractiveness of one in the northern Netherlands. Therefore, as a next step, a full commercial assessment is recommended to be undertaken by a combination of public agencies and interested commercial parties, with the necessary investment capability, to define a project business case.

13 Appendix

13.1 Netherlands’ Energy Background

In 2023 the Netherlands’ energy demand was 955 TWh, dominated by oil and gas making up a combined 75.5% consumption by source[145]. Some of the nation’s largest industries include energy, transport, manufacturing and agriculture. The energy industry produced 57.1 million metric tons of CO_2, the transport industry produced 31 million tonnes and the manufacturing industry produced 26.9 million metric tons of C02, combining to be 115 million tonnes of C02[146], over half of the nation’s total emissions, which was 200 million tonnes of CO_2 in 2019[147]. One of the main ways the Netherlands plans to decarbonise their energy mix is increasing renewables with a big focus on offshore windfarms, namely in the North Sea, similar to Germany.[148]

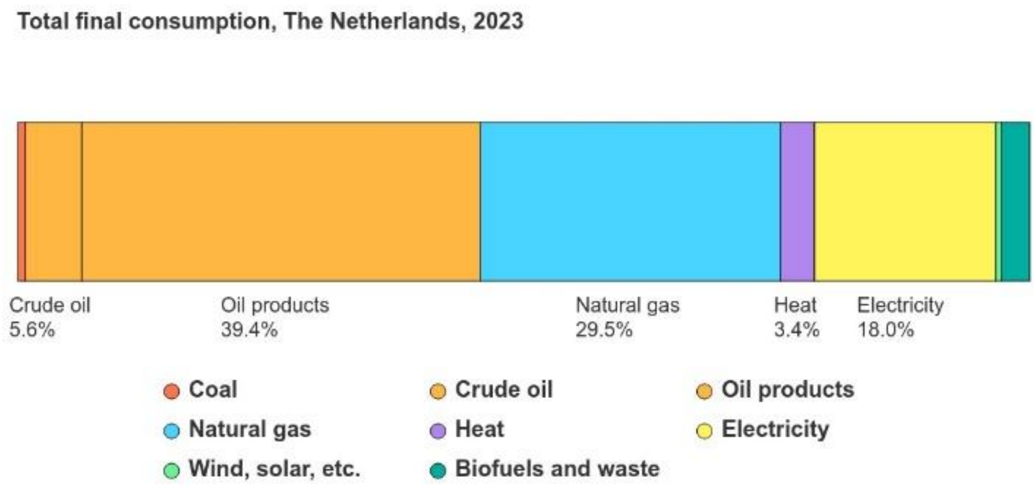

Figure 45. Netherlands energy Mix, 2023[148]

[145] Netherlands: Energy Country Profile. Our World in Data. Accessed at: https://ourworldindata.org/energy/country/netherlands (2023)

[146] Greenhouse gas emissions in the Netherlands in 2019, by sector. Statista. Accessed at: https://www.statista.com/statistics/1288181/greenhouse-gas-emissions-in-netherlands-by-sector/ (2023)

[147] Climate action in the Netherlands. European Parliament. Accessed at: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/696184/EPRS_BRI(2021)696184_EN.pdf (2021)

[148] The Netherlands Understanding Energy End Uses, IEA. Accessed at: https://www.iea.org/countries/the-netherlands/efficiency-demand

13.2 Netherlands' Renewable Energy Goals

As a means of achieving the legally binding climate goal of reducing CO_2 emissions by 55% by 2030, the Dutch government need to implement more offshore wind energy. Thus, the government announced in 2022 a raised offshore wind capacity target from 11 to 21GW by 2030/31, which will supply 16% of energy demand, as well as longer-term targets of 50GW by 2040 and 70GW by 2050[149]. However, renewable electricity on its own won't be able to power the Netherlands due to some of the challenges that storing and supplying renewable electricity comes with. For example, renewable electricity produced by offshore wind turbines can sometimes be greater than the amount of energy that's able to be stored or is being demanded by from users of grid supplied electricity. This would lead to some turbines having to be curtailed (temporarily switched off), which in some cases has caused a financial burden on the public. This is exemplified in Scotland, where in 2023, offshore wind curtailment cost the UK over £670[150]. Therefore, to increase energy security and availability, storing excess energy in another medium is a more practical and a space efficient solution compared to matching electricity storage capacity (which can only be stored for a short time) to offshore wind energy capacity. This ideal energy vector is hydrogen, which can also help overcome the issue of when there isn't enough renewable energy capacity to power the electricity demand.

13.3 Netherlands' Hydrogen Strategy

In response to the European Green deal to make Europe Net-Zero by 2050 and the EU itself introducing their hydrogen strategy, the Netherlands adopted their national hydrogen plan in March 2020 with a target of 4GW installed electrolyser capacity by 2030 (approximately 10% of the total EU target), with the Northern Netherlands region aiming to produce 65 Petajoules of clean hydrogen a year by 2030[151]. This hydrogen will be heavily used to decarbonise public transport, heavy duty vehicles and key aspects of industry including power and chemical production. Netherlands aim to use green hydrogen as the primary way of achieving hydrogen

[149] Plans 2030-2050. Netherlands Enterprise Agency. Accessed at: https://english.rvo.nl/information/offshore-wind-energy/offshore-wind-energy-plans-2030-2050#:~:text=for%202030%2D2050%3F-,Goal,16%25%20of%20Dutch%20energy%20needs. (2023)

[150] Energy Live News. Grid constraints lead to nearly £1bn in curtailment costs on 2023 electricity bills. Accessed at: https://www.energylivenews.com/2024/04/08/grid-constraints-lead-to-nearly-1bn-in-curtailment-costs-on-2023-electricity-bills/#:~:text=The%20majority%20of%20this%20cost,2030%20due%20to%20this%20bottleneck. (2024)

[151] THE NORTHERN NETHERLANDS HYDROGEN INVESTMENT PLAN 2020. New Energy Coalition. Accessed at: https://www.newenergycoalition.org/custom/uploads/2020/10/investment-plan-hydrogen-northern-netherlands-2020-min.pdf (2020)

production targets and decarbonisation, but understand that blue hydrogen will be a key stepping to help catapult this journey and realise the goals of the strategy.

At this point in time, the Netherlands were already the second largest producer of hydrogen in Europe, predominantly from fossil fuels (grey hydrogen). The nation originally investigated hydrogen because of their natural gas history. The natural gas field in Groningen, discovered in 1959, is the largest in Europe, with a volume of 2.74 billion cubic metres. It is estimated around 60% of the natural gas reserves have been recovered[152]. This huge natural gas industry in the Netherlands, with over 7,900 job roles (July, 2023)[153] has given the region extensive knowledge and experience in the gas sector, which can be repurposed and utilised in greener technologies and fuels like hydrogen. Furthermore, the exploitation of the gas field has led to earthquakes, which have caused a total of €1.3 billion[154] in housing and infrastructure damage, with around 3,300 homes being destroyed since the 3.6 Richter scale earthquake in 2012[155].

13.4 How Will the Hydrogen Strategy Targets be Realised?

Earlier in 2023, the Dutch government announced that €7.5bn from their €28.1bn climate package (to reduce CO_2 emissions by at least 55% by 2030, compared to 1990s levels) would be allocated for hydrogen market growth, with a large portion going towards increasing electrolysis capacity in order to meet their 4GW capacity goal by 2030[156]:

- Onshore electrolysis projects of 50MW – €249.9m
- Onshore electrolysis projects of 500MW-1GW – €4.9bn
- Offshore hydrogen production (at offshore windfarms) of projects under 100MW - €380m (capex only)
- Offshore hydrogen production (hydrogen wind farms) of projects 500MW-1GW – €300m

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[152] Locations of major gas fields. Britannica. Accessed at: https://www.britannica.com/science/natural-gas/Location-of-major-gas-fields
[153] More roles in oil and gas in the Netherlands. GlobalData. Accessed at: https://www.energymonitor.ai/news/signal-netherlands-natural-gas-reserves-expire-in-nine-years-threatening-jobs/?cf-view (2023)
[154] Rural Groningen hit by strongest earthquake in five years. Dutch News. Accessed at: https://www.dutchnews.nl/2018/01/groningen-hit-by-strongest-earthquake-in-five-years/#:~:text=The%20biggest%20quake%2C%20in%202012,%E2%82%AC1.3bn%20so%20far. (2018)
[155] Earthquake damage in Groningen: 3,300 buildings demolished since 2012. Structural Engineer. Accessed at: https://www.thestructuralengineer.info/news/earthquake-damage-in-groningen-3300-buildings-demolished-since-2012 (2022)
[156] Dutch Government unveils more than €7.5bn of spending on green hydrogen in new climate package. Hydrogen Insight. Accessed at: https://www.hydrogeninsight.com/policy/dutch-government-unveils-more-than-7-5bn-of-spending-on-green-hydrogen-in-new-climate-package/2-1-1443920 (2023)

- The establishment of knowledge centre for offshore hydrogen to promote knowledge sharing from demonstration projects – €2m
- Hydrogen network at sea – €50m
- De-risking large-scale hydrogen storage – €250m

This package will help develop the infrastructure for Netherlands to reach their targets of a 100% CO_2-free electricity system by 2035. Some money in this plan has been reserved for hydrogen application in heavy road transport, which has already allocated €22m of funding to subsidise the development of hydrogen filling stations suitable for HDVs. This package also reserved money for inland shipping development, where the first hydrogen powered inland cargo vessel was launched earlier in 2023. Additionally, the package will introduce a household energy tax rate for hydrogen which will be lower than that of natural gas, suggesting hydrogen will play a role in heating Dutch homes in the future.

13.5 Green Hydrogen Production in the Netherlands

The Netherlands is strongly focused on hydrogen because it is well positioned to do so. The nation is located close to the demand where the EU aims to have hydrogen replace fossil intensive industries such as refining, fertiliser production and the steel industry. Dutch industry is well experienced with hydrogen, they have optimal locations for storage and an existing infrastructure to help a transition to hydrogen use. Additionally, areas in the Northern Netherlands like Groningen have extensive shorelines and a North Sea territory of 58,000km²,[157] making it an ideal location to deploy offshore wind energy. This is because the Dutch North Sea territory has shallow waters, favourable wind climate and is near large industrial ports who are large energy consumers[158]. With the Netherlands increasing their offshore wind capacity, the Netherlands will be able to produce green hydrogen. In fact, in March 2023, the Dutch government announced plans for a 500MW offshore electrolyser powered by wind turbines, where the green hydrogen would be pumped to the shore by pipeline. The government also announced plans for a 600MW facility back in 2022, which would by powered by offshore wind energy but the hydrogen would be produced by an onshore electrolyser[159].

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[157] Integrated Management Plan of the North Sea 2015 (NL). European MSP Platform. Accessed at: https://maritime-spatial-planning.ec.europa.eu/practices/integrated-management-plan-north-sea-2015-nl

[158] Offshore wind energy. Government of Netherlands. Accessed at: https://www.government.nl/topics/renewable-energy/offshore-wind-energy#:~:text=its%20relatively%20shallow%20waters%3B,and%20(industrial)%20energy%20consumers.

[159] Tender for 500MW offshore green hydrogen project in North Sea announced by Dutch government. Hydrogen Insight. Accessed at: https://www.hydrogeninsight.com/production/tender-for-500mw-offshore-green-hydrogen-project-in-north-sea-announced-by-dutch-government/2-1-1422681 (2023)

The Northern Netherlands is also home to Europe's first hydrogen-valley, HEAVENN, which is a regionalised hydrogen value chain that interconnects different aspects of hydrogen applications including the built environment (energy for houses), mobility, production and infrastructure for hydrogen. The project has an overall budget of €96 million including €20 million contribution from the EU. The project started in 2020 and will run until the end of 2025. The hydrogen valley principal is designed to build up hydrogen knowhow and confidence amongst all types of stakeholders right throughout the hydrogen value chain from production, distribution and end use like mobility and power. Therefore, by carrying out the groundwork HEAVENN is paving the way for the next step of hydrogen applications in the local region, including the introduction of wider use of LH_2.

13.6 How Can Hydrogen Decarbonise the Netherland's Most Polluting and Largest Sectors?

To understand how LH_2 in the Netherlands can leapfrog their decarbonisation journey, we must look into the role of and current uses of gaseous hydrogen to grasp the hydrogen landscape and where LH_2 opportunities present themselves, along with added operational benefits from LH_2 storage or applications.

13.6.1 Energy production

Hydrogen is a zero-carbon emission energy vector that can either be used through fuel cells or combustion. By increasing the amount of energy produced from hydrogen instead fossil intensive fuels like gas, coal and oil, the energy industry can be decarbonised over time, once the infrastructure is put in place. Following the Russian invasion of Ukraine and needing to reduce dependency on Russian oil and gas there is an opportunity to repurpose pipelines for a more sustainable gas. The Netherlands already have plans to construct over 1,000km of dedicated pipeline for hydrogen built by Gasunie. The pipeline will be fully operational from 2030 linking major industry hubs in Netherlands, Germany and Belgium, where 85% of the network will use retrofitted natural gas lines, which makes the project 75% cheaper than if it were to build new infrastructure[160]. With this plan in mind, the country's dense NG grid of 136,000km could eventually be entirely retrofitted for hydrogen distribution to become a key part of Netherland's hydrogen backbone by 2027. This will feasibly help decarbonise heating supplies currently

[160] Gasunie takes FID for 1st section of EUR-1.5bn Dutch hydrogen network. Renewables Now. Accessed at: https://renewablesnow.com/news/gasunie-takes-fid-for-1st-section-of-eur-15bn-dutch-hydrogen-network-826970/ (2023)

running on natural gas, which could be switched over to hydrogen, or used in combination. Part of goal for the Dutch hydrogen backbone is to replace fossil intensive feedstocks in the production of chemicals and other industrial processes with hydrogen alternatives. Hydrogen can also help replace fossil fuel powered electricity plants that help manage electrical fluctuations on a quick response basis. Trade and investment partnerships between the Dutch and German governments have meant that these two countries have been the primary drivers of the European hydrogen backbone as they are now the leading consumers of hydrogen in Europe, making them two of the largest players in the market, positioning them for trading opportunities to other hydrogen importing and exporting nations across the member states and the world, with their knowledge and expertise helping develop other hydrogen projects. This is exemplified by the Netherlands and German's investment within the H2Global mechanism, which is a European led collaboration that incentivises the development of overseas value chains for domestic imports. The Dutch government has planned to open tenders for green hydrogen import in early 2024 backed by €300m in subsidies[161], showing the scale of this mechanism and commitment to import targets to achieve a greener energy mix.

13.6.2 Transport

As mentioned previously, hydrogen in transport is best used in larger vehicles such as HDVs, aviation and maritime. FCEVs in the form of buses have been targeted specifically in the Netherlands, with public acceptance of this technology growing more and more, as there are now over 30 operational buses in the region. Hydrogen is favoured in heavy duty vehicles over BEVs because they have much greater power to weight ratios and can be charged in less than 10 minutes compared to hours for battery powered buses. Seeing the benefit of hydrogen powered vehicles, the Netherlands set out in their National Climate Agreement to see 50 refuelling stations, 15,000 fuel cell vehicles and 3,000 HDVs by 2025[162].

Figure 46. Van Hool FCEV bus for QBuzz, Netherlands[163]

[161] Netherlands plans green hydrogen import auction by early 2024, backed by €300m of subsidies. Hydrogen Insight. Accessed at: https://www.hydrogeninsight.com/policy/netherlands-plans-green-hydrogen-import-auction-by-early-2024-backed-by-300m-of-subsidies/2-1-1435546 (2023)

[162] HYDROGEN LAW, REGULATIONS & STRATEGY IN THE NETHERLANDS. CMS. Accessed at: https://cms.law/en/int/expert-guides/cms-expert-guide-to-hydrogen/netherlands

LH_2 enabled vehicles will allow for the longer distance journeys but will require a source in order to enable fuel security for refuelling to allow for smooth day to day operations.[163]

The Netherlands also has over 6,000km of navigable waterways[164] and several major ports, which presents a significant opportunity for hydrogen to decarbonise their maritime sector, which produces significant pollution. Furthermore, North of the Northern Netherlands are the Wadden Islands, which are accessible by Ferry and has approximately 3 million visitor arrivals every year[165], resulting is significant number of ferry journeys every day. LH_2 could be used to decarbonise this sector by using similar models to that of the MF Hydra in Norway, which the Netherlands can use their existing network to Norway to leverage expertise and knowhow to penetrate this market.

13.6.3 Manufacturing

The largest industries in the Dutch manufacturing sector are refineries and chemistry (23%), electronics, machinery (22%), food and beverages (20%), basic metals and products (12%). Hydrogen can help decarbonise these sectors in several ways.

The chemical industry is one of the Netherland's largest sectors and with many of the chemical processes requiring high-temperature heat. Such temperatures can be challenging or infeasible to electrify, meaning a renewable fuel such as hydrogen is needed to replace fossil fuel currently in use. Additionally, chemicals that require hydrogen in their compounds such as ammonia (NH_3) and methanol (CH3OH) can swap out grey hydrogen for green hydrogen in order to reduce the chemical's carbon footprint.

The Netherlands is in the top 10 countries for semiconductor manufacturing, which as highlighted earlier, requires extremely pure hydrogen to process wafers. If this hydrogen were to come from renewable sources the industry's carbon footprint would decrease. The Netherland's has four semiconductor fabrication plants, which demand a large amount of energy to complete the complex and long manufacturing process for semiconductors. These plants could be powered by hydrogen through fuel cells for electricity in the future[166].

[163] Van Hool FCEV bus for Qbuzz, UKH2 Mobility. Accessed at: https://www.ukh2mobility.co.uk/wp-content/uploads/2020/01/vanhool_.jpg
[164] CAptain's Mate of the Month – Rotterdam, Netherlands. Cruising Association. Accessed at: https://www.theca.org.uk/news/captains-mate-of-the-month-rotterdam#:~:text=Cruising%20the%20Netherlands%20with%20the,/public/sections/eiw (2024)
[165] Wadden Sea Quality Status Report. Wadden Sea World Heritage. Accessed at: https://qsr.waddensea-worldheritage.org/reports/tourism#:~:text=The%20Wadden%20Sea%20World%20Heritage%20region%20is%20a%20popular%20destination,in%20Denmark%20and%20the%20Netherlands. (2021)
[166] Semiconductor Manufacturing by Country 2023. World Population Review. Accessed at: https://worldpopulationreview.com/country-rankings/semiconductor-manufacturing-by-country (2023)

In 2021, the Dutch steel industry produced around 6.6 million tonnes of crude steel. But when produced using coal-based production methods it's an extremely carbon emitting industry, which is the most prominent method in today's industry. However, hydrogen can radically change how steel is produced and significantly reduce emissions. This process is known as Direct Reduced Iron, which reacts hydrogen with iron ore. This process produces iron and water instead of iron and CO_2 as a byproduct. Additionally, this process occurs at a lower temperature, requiring less energy[167].

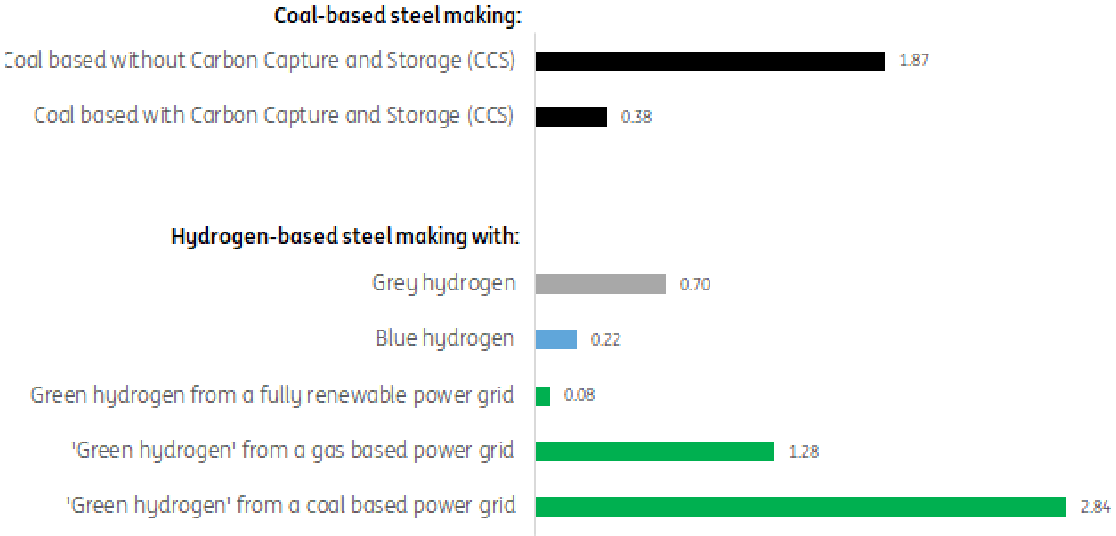

Figure 47. CO2 emissions (kg) per kilogram of steel[167]

13.6.4 Agriculture

The agriculture industry is a very polluting sector in the Netherlands for NOx and CO_2 emissions, with the government having very strict nitrogen emission limits, which could affect agriculture businesses in the future if these emission targets aren't met. Hydrogen can help reduce these emissions by switching Heavy machinery to hydrogen power, such as hydrogen tractors. For example, the world's first hydrogen tractor, the H_2 Dual

Figure 48. Friesland Campina hydrogen truck[169]

[167] Hydrogen sparks change for the future of green steel production. ING. Accessed at: https://www.ing.com/Newsroom/News/Hydrogen-sparks-change-for-the-future-of-green-steel-production.htm#:~:text=The%20magic%20of%20hydrogen%20is,natural%20gas%20instead%20of%20hydrogen. (2023)

Power offers the ability to run on hydrogen and diesel, significantly reducing CO_2 and NOx emissions and with zero loss in torque[168]. Additionally, distribution vehicles can also switch to hydrogen. An example of this is Friesland Campina, who in 2021 rolled out a hydrogen powered truck to fuel their milk distribution service[169]. Hydrogen is also being looked at as fuel for high-temperature heat applications, which could be used for pasteurization. This would lower the use of natural gas in the sector, which would reduce both CO_2 and NOx emissions. A consortium with the project name HYREADY is looking at developing industrial burners that can run on natural gas with hydrogen blends of up to 100% in the Netherlands[170], to which Friesland Campina are hoping will enable them to use hydrogen in their high-temperature heat farming practices. These emission savings in mobility and processes can enable other aspects of agriculture such as livestock to remain unaffected by NOx emission limits. Furthermore, agriculture requires a lot of fertilizer to help crops grow, however these fertilizers are often very emitting in their production process and in their end use. Ammonia is one of these fertilizers and in 2021 over 90% of Ammonia was produced using steam reformation, a fossil fuel intensive process producing 1.8% of global CO_2 emissions[171]. However, with the Netherland's focus on green hydrogen production and its applications, green ammonia can be produced from hydrogen made by electrolysis creating a zero-carbon fertilizer and massively decarbonising the agriculture industry.

13.7 Hydrogen projects in the Northern Netherlands

There are currently more than 50 hydrogen projects for various parts of the hydrogen value chain planned and being developed in the Northern Netherlands for hydrogen production, transport, storage, industry and power, with the majority constructing electrolysis plants to increase supply of green hydrogen, powered by offshore wind energy. One of the first and larger renewable hydrogen projects in the Netherlands is the HyNetherlands project which aims to initialise a long-term renewable hydrogen value chain across the Netherlands, aiming to have a 100MW electrolyser capacity by 2028, 400-800 MW post 2030 and 1.5-1.85GW post 2035. Part of the goal of this project is to improve the overall efficiency of water electrolysis against the current standards and set a basis for the Dutch hydrogen backbone spreading over a national and European level[172]. Another production project includes the 20MW DJEWELS electrolyser project

168 H2 Dual Power. Blue Fuel Solutions. Accessed at: https://h2dualpower.com/en
169 FrieslandCampina Rolls Out Hydrogen-Powered Milk Truck. European Supermarket Magazine. Accessed at: https://www.esmmagazine.com/supply-chain/frieslandcampina-rolls-hydrogen-powered-milk-truck-139939 (2021)
170 Hydrogen as a fuel for high-temperature heating processes. DNV. Accessed at: https://www.dnv.com/article/hydrogen-as-a-fuel-for-high-temperature-heating-processes-219385
171 Ammonia: zero-carbon fertiliser, fuel and energy store. The Royal Society. Accessed at: https://royalsociety.org/-/media/policy/projects/green-ammonia/green-ammonia-policy-briefing.pdf
172 A gigawatt scale green hydrogen value chain. HyNetherlands. Accessed at: https://hynetherlands.nl/

in Delfzijl, which will provide 3,000 tons of green hydrogen a year, aiming to reduce CO_2 emissions by up 27,000 tons per year in combined activities with BioMCN, who will produce renewable methanol with the green H2[173]. Green hydrogen production isn't the only colour being targeted, as there are several blue hydrogen production facilities being design for Rotterdam, including the Porthos project which will develop CCUS infrastructure capable of sequestrating 2.5 million tons of CO_2 per year costing >€20m and the H-vision project which will build several facilities to produce industrial blue hydrogen. Blue hydrogen is on average 59% cheaper than green hydrogen[174], which makes it much more appealing to produce in the short term and if used as the feedstock for LH_2 production, it can reduce LH_2s levelised cost, making it more feasible to produce and penetrate the markets at a faster rate. Blue hydrogen also has the advantage of having continuous production compared to green hydrogen, which relies on availability of renewable energy, which can be intermittent on calm or cloudy days depending on if wind or solar is used (unless electrolysers are powered by grid connection). Because of this intermittency, grid power is often supplemented by fossil-generated electricity in the evenings and nights due to the lack of sunlight and often calmer winds, adding unabated carbon intensity to the "green" hydrogen. However, recent peaks in natural gas prices reaching €339 per MWh in August 2022 as a result of the Russian Invasion of Ukraine affecting fuel security and prices, show that blue hydrogen in the future will become more expensive to make as fossil fuels are taxed more and become shorter in supply as demand shifts towards greener energy such as green hydrogen or renewable electricity. Additionally, the expected carbon capture rate of blue hydrogen projects is expected to be around 90-98%, but 13 of the major global CCUS projects around the world representing 55% of total sequestration have either failed to meet their targets or have captured significantly less than expected. For example, the world's only large power station with CCS, Boundary Dam in Saskatchewan, Canada, has captured about 50 per cent less than planned[175], showing that the CCUS industry has a long way to go in terms of efficiency to prove it has serious large-scale decarbonisation potential.

On a more end user basis, one of the biggest hydrogen mobility projects linking Netherlands, Belgium and west Germany is the HyTrucks project, which has a consortium of over 60 companies, aiming to have 1000 hydrogen powered trucks on the roads in these regions by 2025. The parties involved makeup of all aspects of the value chain in order for this project to be

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[173] BioMCN to produce renewable methanol with green hydrogen. Nouryon. Accessed at: https://www.nouryon.com/news-and-events/news-overview/2019/biomcn-to-produce-renewable-methanol-with-green-hydrogen/ (2019)
[174] Blue hydrogen cheaper than green H2 in all markets except China amid falling gas prices: BNEF. Hydrogen Insight. Accessed at: https://www.hydrogeninsight.com/production/blue-hydrogen-cheaper-than-green-h2-in-all-markets-except-china-amid-falling-gas-prices-bnef/2-1-1486049 (2023)
[175] Most major carbon capture and storage projects haven't met targets. NewScientist. Accessed at: https://www.newscientist.com/article/2336018-most-major-carbon-capture-and-storage-projects-havent-met-targets/ (2022)

realised, including hydrogen suppliers, truck manufacturers, operators of filling stations, transporters and shippers[176]. Some hydrogen is also being produced with specific industry uses in mind, including the H2ermes project, which will develop a 100MW electrolyser in Amsterdam for Tata steel production[177]. The hydrogen produced by the electrolyser will allow Tata, who are responsible for 3.8% of Dutch emissions in this sector, to produce steel using the Direct Reduced Iron technique, which enables iron production using electric arc furnaces (powered by renewable hydrogen)[178]. This project is a flagship project of the Hydrogen Hub Amsterdam.

[176] HyTrucks – Hydrogen Road Transport is well on its Way – TTM. Hydrogen Central. Accessed at: https://hydrogen-central.com/hydrogen-road-transport/ (2022)
[177] Project. H2ermes. Accessed at: https://h2ermes.nl/project-en/
[178] Hydrogen route – TATA steel. Port of Amsterdam. Accessed at: https://msp365.nl/nzkg/

Abbreviations

Abbreviation	Meaning
°C	Degrees Celsius
AFIR	Alternative Fuels Infrastructure Regulation
API	American Petroleum Institute
CAPEX	Capital Expenditure
CCUS	Carbon Capture Storage and Utilisation
CHEETA	Centre for High-Efficiency Electrical Technologies for Aircraft
CHC	Cryogenic Hydrogen Compressor
CH_3OH	Methanol
CO2	Carbon Dioxide
CRF	Capital Recovery Factor
EN	European Norms
ESA	European Space Agency
EU	European Union
EUR	Euros
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FID	Final Investment Decision
FPS	Future Proof Shipping
FSRU	Floating Storage and Regasification Unit
GH_2	Gaseous Hydrogen
GHG	Green House Gas
GW	Gigawatt
GWP	Global Warming Potential
H2	Hydrogen
H2V	Hydrogen Valley
HDV	Heavy Duty Vehicle
HESC	Hydrogen Energy Supply Chain
HFO	Heavy Fuel Oil
HICE	Hydrogen Internal Combustion Engine
HRS	Hydrogen Refuelling Station
IEA	International Energy Agency
IGCs	Industrial Gas Companies
IPCEI	Important Projects of Common European Interest

ISO	International Organisation for Standards
K	Kelvin
kg	Kilogram
Km	kilometre
kWh	Kilowatt hour
LCA	Life Cycle Analysis
LED	Light-Emitting Diode
LH_2	Liquid Hydrogen
LNG	Liquid Natural Gas
LOHC	Liquid Organic Hydrogen Carriers
m^3	Metres cubed
MoU	Memorandum of Understanding
MPa	Megapascal
MRI	Magnetic Resonance Imaging
MT	Megatonne
Mtpa	Megatonne per annum
MW	Megawatt
NEW	North West Europe
NH_3	Ammonia
NMR	Nuclear Magnetic Resonance
NOx	Nitrogen Oxide
PoH	Port of Hamburg
PoR	Port of Rotterdam
PoW	Port of Wilhelmshaven
PRSDS	Power Reactant Storage and Distribution System
RES	Renewable Energy Sources
RFNBO	Renewable Fuels of Non-Biological Origin
RTP	Room Temperature Pressure
SAF	Sustainable Aviation Fuels
SMR	Steam Methane Reformer
TEN-T	Trans-European Transport Network
tpd	Tonnes per day
TRL	Technology Readiness Level
TWh	Terawatt hour
UK	United Kingdom
US / USA	United States of America