D6.7 Hydrogen Export to Neighboring regions from the HEAVENN 'Hydrogen Valley' Region

An assessment of the European hydrogen landscape to understand the potential to export hydrogen from the HEAVENN region.

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HyEnergy is an experienced consultancy with over 50 years of expertise within the global hydrogen and renewable energy sectors. It supports stakeholders including industry, local/regional public sector organisations and national governments in transitioning to sustainable energy solutions.

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Executive Summary

This report reviews and analyses the potential to export hydrogen from the HEAVENN region to neighbouring areas including to the Netherlands, Germany, and the UK. To best assess this opportunity, a dual investigative approach has been undertaken. This includes a market analysis of surrounding areas to ascertain the demand for importing hydrogen in the medium and long-term, and a cost analysis to understand the competitiveness of exported hydrogen from the HEAVENN region.

Seven different scenarios have been created to assess the cost of hydrogen to customers from the HEAVENN region. This includes four production scenarios:

1. **Green Local** – Green hydrogen produced at the port of Eemshaven via dedicated renewables.
2. **Blue Historic Local –** blue hydrogen produced at the port of Eemshaven using historic natural gas prices (pre-energy crisis).
3. **Blue Modern Local** – blue hydrogen produced at the port of Eemshaven, using modern-day natural gas prices.
4. **Green International** – Green hydrogen that is converted to ammonia and shipped from Saudi Arabia to Eemshaven. Ammonia is reconverted to hydrogen at Eemshaven.

Along with three varied distribution scenarios:

1. **Regional Compression Hub** – Hydrogen that is piped an average of 300km to a regional compression hub before it used to fill a gaseous tube trailer. This tube trailer then travels an average of 25km to make a delivery to its end-users.
2. **Direct Industrial Connection –** Hydrogen that is directly piped to an industrial end user via a 300km pipeline.
3. **Liquid Hydrogen Distribution** – Hydrogen that is liquefied at the port of Eemshaven and distributed by the liquid tanker to end-users and average distance of 300km away.

This report has found that there is considerable opportunity for the HEAVENN region to provide hydrogen to its near neighbours both through the use of national distribution systems, and continental initiatives such as the European Hydrogen Backbone. The amount of hydrogen available, both from local production and the potential to supplement these with further imports, exceeds local demand profiles. However, to gain access to international value chains, local policy makers must position critical local infrastructure such as the port of Eemshaven and Delfzijl chemical cluster to benefit from the import of hydrogen. This must occur quickly to avoid being undermined by other hydrogen interested ports such as Rotterdam or Hamburg.

Therefore, key to developing a position in a wider hydrogen supply market will be the support from the region and nationally to develop hydrogen the highlighted facilitating infrastructure across the Eemshaven/Delfzijl corridor.

Context - The HEAVENN Project

The northern Netherlands is an area built on its energetic prowess. Its coastline has historically been occupied with multiple power generation stations and it is home to some of the largest natural gas reserves in the whole of Europe. These resources have fed a wealth of industry within the region and have also been key to addressing the rest of the Netherland's energy demand via robust, secure, and wide-reaching transmission infrastructure. However, the long-term extraction of natural gas which has resulted in serious subsidence issues within the area coupled with a drive to decarbonise means the northern Netherlands must change its ways, and quickly.

The CEF funded TSO2020 project, HEAVENN's precursor project, assessed the options available to transmissions system operators to accelerate low-carbon investments in the field of trans-European networks in transport, energy, and telecommunications. Hydrogen was investigated as a potential energy vector that could help link the electricity, and power sectors by addressing intermittent renewable power generation whilst also increasing green energy penetration. It was found that the region's renewable resources, natural gas infrastructure, and local salt caverns could provide a suitable opportunity for hydrogen deployment, particularly when utilising existing industrial demand as a catalyst to deliver further hydrogen deployment within mobility and heating.

Step forward the HEAVENN project. HEAVENN – Hydrogen Energy Applications in Valley Environments for Northern Netherlands - is a large-scale programme of demonstration projects bringing together the core hydrogen supply chain elements of production, distribution, storage and local end-use of hydrogen in a fully-integrated and functioning "hydrogen valley" (H2V), that can serve as a blueprint for replication across Europe and beyond. The concept is based on the deployment and integration of existing and planned project clusters across six locations in the Northern Netherlands, namely Eemshaven, Delfzijl, Zuidwending, Emmen, Hoogeveen and Groningen.

The project's main goal is to utilise low-carbon hydrogen across the entire value chain, while developing replicable business models for wide-scale commercial deployment of hydrogen across the entire regional energy system. HEAVENN aims to maximise the integration of abundant renewable energy sources available in the region, both onshore (wind and solar) and offshore wind, using hydrogen as: (i) a storage medium to manage intermittent and constrained renewable inputs in the electricity grid; and (ii) an energy vector for further integration of renewable inputs and decarbonisation across other energy sectors beyond electricity, namely industry, heat and transportation.

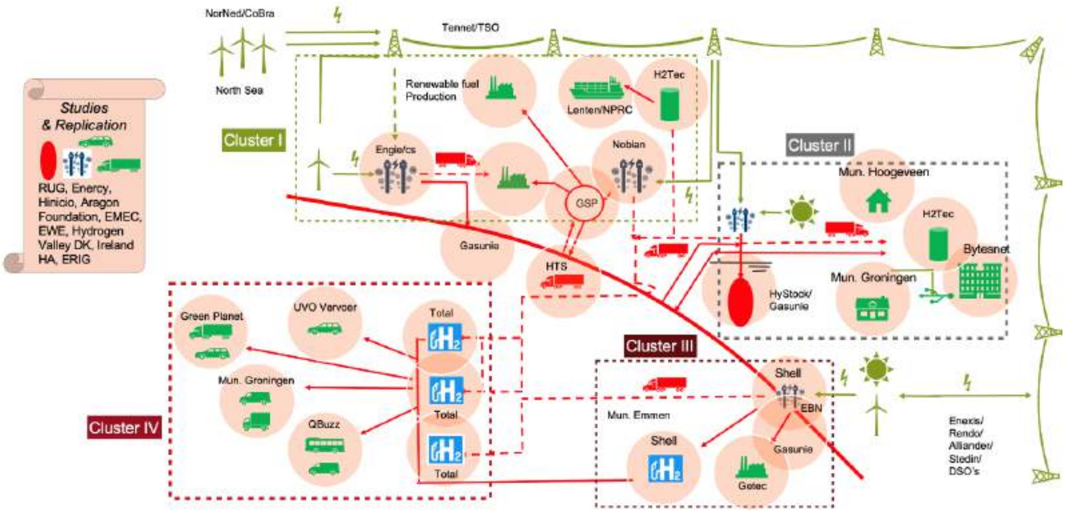

Figure 1*: The HEAVENN Project Schematic*

Within the project, Work Package 6 (WP6) – Studies Enabling Future Hydrogen Roll Out – focuses on maximising the impact of the HEAVENN project. Through this work package a number of detailed studies will be produced, spanning all areas of the hydrogen value chain (Process; pre-engineering; renewable sector coupling etc.). This will be used to build a sufficient evidence base to further interconnecting infrastructure and hydrogen market penetration in the future in a way that de-risks any future sector investment both within the HEAVENN region and further afield. WP6 will establish the framework for regional, cross-border, scale up of hydrogen activities including production, storage and distribution, and applications as well as exploring the potential of the HEAVENN region to export hydrogen to neighbouring areas.

The HEAVENN region has recognised it has all the key infrastructure and building blocks to allow for export of large volumes of green hydrogen to neighbouring regions – large scale green hydrogen production technologies; ideal deployment locations; underground storage opportunities; access to pan-European natural gas infrastructure and public sector buy-in. Within this study the potential export market will be assessed for 2030 and 2050 scenarios, providing further market data evidence for investing in green hydrogen and transmission systems within the region.

Introduction

The environment has become one of the most pressing issues on the global political agenda. Academics and activists have successfully convinced policy makers of the need to act and reduce emissions leading to widespread legally binding climate agreements, showcasing the global desire to change. However, the pace, cost, and responsibility of this change is still experiencing resistance from independent bodies as current strategies are unlikely to obtain the goal of 'limiting global warming to well below 2 ^{O}C, preferably to 1.5 ^{O}C' set out in The Paris Agreement by 2050.

Considerable progress has been made across the world reducing the carbon-intensity of electricity grids through the integration of large-scale renewables. However, this poses two critical issues:

1. Grids today already struggle to deal with the intermittency of GW-scale deployments of renewable electricity. This is likely to worsen as the next phase of renewables rollout is realised.
2. Electricity only accounts for 23.2% of the EU's final energy consumption[1] and is only responsible for a small amount of industrial, mobility, and built environment energy demand.

Therefore, there is a clear need for alternative energy solutions which help to alleviate renewable intermittency whilst addressing the energy demand exhibited by solid fuels, oil, petroleum, and natural gas products - >55% of final energy consumption. Furthermore, with recent geopolitical events, such as the Russian invasion of Ukraine, showcasing the fragility of the global energy landscape, the need for moving at pace and scale has been exemplified.

Recognising this, energy vectors, such as hydrogen, have received a great amount of global interest. Their ability to reduce emissions, by maximising the capture of renewable energy and its penetration into hard-to-abate sectors, and increase energy security, through long-term storage of energy, have resulted in a worldwide momentum surrounding these technologies. For instance, 27 countries have now released hydrogen strategies, and hydrogen has been heavily included within recent EU climate legislation. In fact, the RePowerEU initiative almost quadrupled the EU's low-carbon hydrogen ambitions from an initial 5.6 Mt by 2030, to 20 Mt in the same timeframe – with half being produced domestically, and the other half imported – including 2.5-fold increase in its planned use in the transport sector.

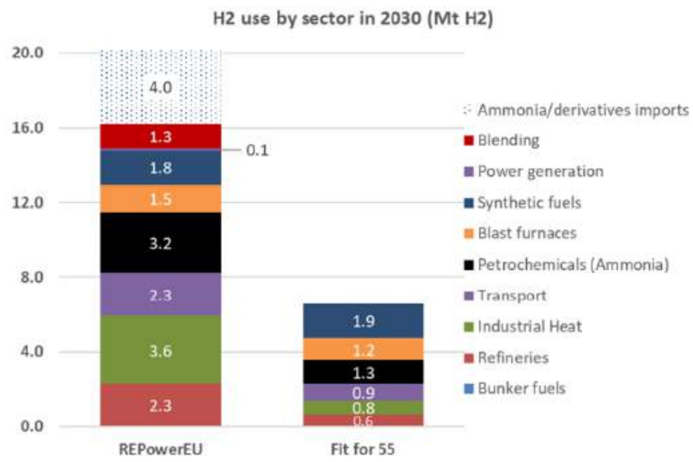

Figure 2: *Hydrogen use by sector in 2030 expectations following the release of Fit-for-55 and REPowerEU – EnergyPost.eu*

[1] Eurostat. Energy statistics – an overview. Accessed as: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#Non-energy_consumption (2022).

As the EU's first hydrogen valley, the HEAVENN project is dedicated to realising commercial and innovative solutions to enable a continent-wide hydrogen economy. This study will assess the role of the project region to act as both a production and import location of low-carbon hydrogen, with the purpose of distributing to surrounding locations to help satisfy and grow regional hydrogen demand across multiple end-use sectors.

Hydrogen sector drivers

Hydrogen is an energy vector that enables greater emissions savings and renewable energy penetration into hard-to-abate sectors when made via low-carbon routes. As can be seen through recent policy developments, whether that be the Fit-for-55 package, or the REPowerEU initiative, hydrogen will play a key role in addressing the continent's future energy needs and ensuring wide-spread decarbonisation. The decentralised nature of energy production and demand centres has led to the development of energy vector value chains. This approach enables the distribution, storage (short and long-duration), and use of energy in a molecular form - preventing a reliance on already stressed electrical infrastructure. Europe, particularly countries based in the northwest, see hydrogen and energy vectors as a way to secure foreign energy from all across the globe. These countries have already started exploring agreements with renewable hotspots to obtain more energy for their domestic economies, including:

- **Germany** – Germany expects its domestic hydrogen demand to grow from roughly 55 TWh in 2020 to between 90 – 110 TWh by 2030. Local production, however, is only expected to reach 14 TWh in the same timeframe[2]. Thus, Germany founded the H2Global instrument[3] to help assess and develop international power-to-X pathways and technologies to benefit Germany through foreign trade partnerships. Meanwhile, Germany has also been investigating individual partnerships with countries based across all continents. For instance, at COP27, Chancellor Scholz and Canadian Prime Minister Justin Trudeau, signed an agreement to form the 'Canada-Germany Hydrogen Alliance' which will commit the two countries to synergistically supporting hydrogen value chains leading to the export of clean Canadian hydrogen to Germany by 2025[4].
- **Netherlands** – the Netherlands have chosen to explore international hydrogen co-operation via the traditional route of Memorandums of Understanding (MoUs) and bilateral agreements. The first of which was, the MoU signed with Portugal in the latter part of 2020 to develop an export-import chain between the two countries by 2030[5], with the ports of Sines and Rotterdam playing key roles. The Netherlands has since made joint statements with Chile to collaborate in the field of green hydrogen import, and export, and has signed R&D agreements with the United States, and produced white papers with India too.
- **UK** – the UK on the other hand, has taken a different approach, instead focusing its collaboration on the private sector, rather than direct agreements with foreign governments. JCB, and its partner Ryze Hydrogen, have signed a multibillion-pound deal to import and supply hydrogen produced by Australian-based Fortescue Future Industries (FFI)[6]. The deal, which is a 'first-of-its-kind partnership' will see JCB take 10% of the green

[2] CSIS. Germany's Hydrogen Industrial Strategy. Accessed at: https://www.csis.org/analysis/germanys-hydrogen-industrial-strategy (2021).
[3] H2Global Stiftung. The H2Global Mechanism. Accessed at: https://www.h2global-stiftung.com/project/h2g-mechanism (2022).
[4] Government of Canada. Canada and Germany Sign Agreement to Enhance Germany Energy Security with Clean Canadian Hydrogen. Accessed at: https://www.canada.ca/en/natural-resources-canada/news/2022/08/canada-and-germany-sign-agreement-to-enhance-german-energy-security-with-clean-canadian-hydrogen.html (2020).
[5] Government of the Netherlands. Portugal and the Netherlands strengthen bilateral cooperation of green hydrogen. Accessed at: https://www.government.nl/latest/news/2020/09/23/portugal-and-the-netherlands-strengthen-bilateral-cooperation-on-green-hydrogen (2020).
[6] BBC. JCB signs green hydrogen deal worth billions. Accessed at: https://www.bbc.co.uk/news/uk-59107805 (2021).

hydrogen FFI make, which will mostly be imported. However, international public sector collaboration in the UK remains limited.

This imported hydrogen will likely be used to satisfy the demand of hard-to-abate sectors. Industry, transport, and heat, to name just a few, are difficult to electrify and therefore will need to decarbonise via the use of energy vectors. In the following section of this report, the market, sectoral, and policy drivers that are responsible for the increased momentum surrounding hydrogen will be discussed.

Industrial clusters and Ports

Global hydrogen demand amounted to 94 million tonnes in 2021[7]. Industrial demand accounts for over 99% of this figure due to the importance of hydrogen-related industry including refining (42.3%), chemicals production – especially ammonia (36.0%) and methanol (15.5%) – and iron and steel production (5.5%).

These Energy intensive processes, which utilise hydrogen as a fundamental chemical building block and heat source, require large-scale, robust, and continuous hydrogen supply. Currently, the majority of this hydrogen is produced via fossil-fuel derived methods resulting in roughly 900 Mt of CO_2 emissions[7]. Therefore, Industrial demand is *the* key driver for the introduction of large-scale low-carbon hydrogen supply chains.

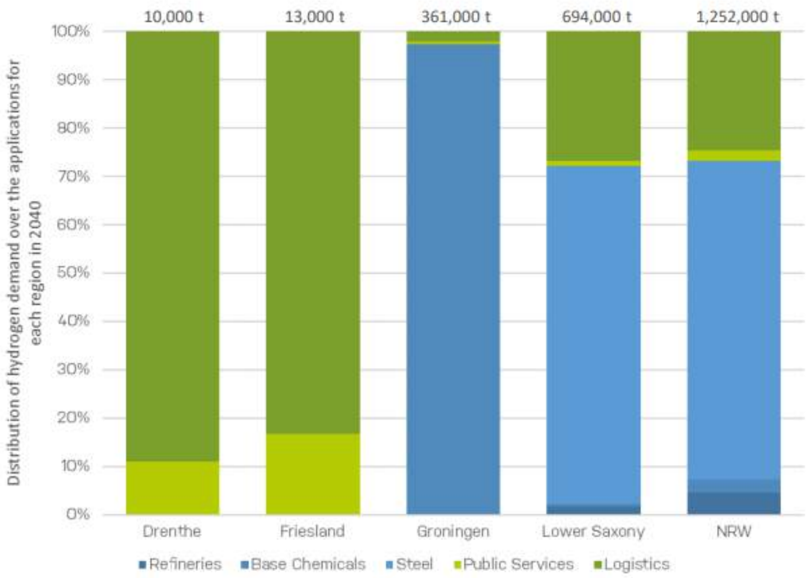

Figure 3*: Expected Hydrogen demand by Sector in 2040, including an at least 50% increase in hydrogen demand based on 2030 projects* – Energy Engineers

Historically, low-carbon hydrogen production hubs have struggled to secure investment to scale their facilities due to a lack of bankable long-term offtake agreements. Thus, by partnering with the largest and most reliable consumers of hydrogen – industry - they can ease investors' worries.

This approach has become integral to both individual low carbon hydrogen projects, as HEAVENN pioneered, and national hydrogen strategies. The UK's hydrogen strategy is almost entirely based upon the mitigation of grey hydrogen with low-carbon alternatives across industrial clusters – particularly along the country's east coast which can access carbon sequestration locations in the North Sea. Similarly, Spain's hydrogen roadmap has implemented an obligation to replace 25% of industrially used hydrogen with renewable hydrogen by 2030[8], the country's principal end-user target. The EC, recognising the emissions-saving opportunity of industrial hydrogen use, implemented a similar obligation as part of the Fit-for-55 package. 35% of all hydrogen used in

[7] IEA. Hydrogen. Accessed at: https://www.iea.org/reports/hydrogen (2022).
[8] Watson Farley & Williams. The Spanish Hydrogen Strategy. Accessed at: https://www.wfw.com/articles/the-spanish-hydrogen-strategy/ (2021).

industry across the EU must be renewable by 2030, rising to 50% by 2035. To completely replace grey industrial hydrogen use, however, particularly within northwest Europe, considerable volumes of low-carbon hydrogen will need to be imported. As such, the initial 1 Mt imported hydrogen target included as part of the Fit-for-55 package, as can be seen in Figure 4, has been dramatically increased to 10 Mt within REPowerEU by 2030[9] – highlighting the importance of international value chains. However, these value chains have not yet reached a position of market deployment and are instead being investigated as part of feasibility studies and MoUs.

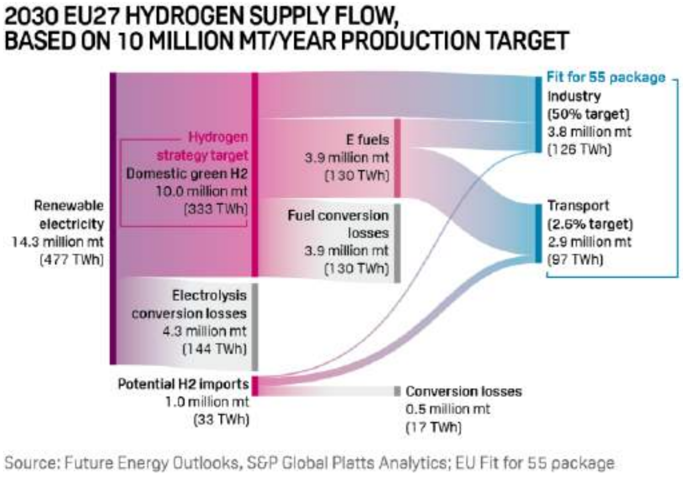

Figure 4*: Fit-for-55 EU hydrogen targets*

International value chains will see an added emphasis placed on the role of industrial clusters, especially those based close to ports, as processing locations for importing and exporting hydrogen. Processing comes in several forms in the hydrogen sector – decanting, transformation, liquefying, dissociating, and compressing (etc.). Many of these procedures can only be undertaken in large, specialised spaces due to their safety requirements and exclusion zones, and thus cannot be based in busy urban locations. For that reason, industrial clusters and ports are likely to house these processes. These sites typically have well connected infrastructure, both upstream and downstream, and in the case of ports, enable the effective movement and trade of energy internationally – key to ensuring access to the lowest cost of hydrogen from around the world. Ports already play an integral role energetically in Europe. For instance, 13%[10] of the continent's energy demand reaches Europe via the port of Rotterdam alone. If Europe's ports are to continue this role, they will need to increase their competencies to include hydrogen energy processes as its prevalence increases.

Within the HEAVENN region, the Port of Eemshaven could undertake a similar role. Eemshaven will almost certainly be used as a onshoring location for local offshore renewable deployments, but by expanding this energetic position to hydrogen, and other hydrogen derived fuels and molecules such as ammonia, the port could hold a key position regarding the integration of domestic and international energy value chains with downstream end-users. The port's natural gas infrastructure could be repurposed to enable cost-effective distribution of hydrogen to locations such as the Delfzijl chemical cluster, which could utilise low-carbon hydrogen to switch existing feedstocks in

[9] Energypost.eu. How to ramp up Hydrogen under the new REPowerEU Targets. Accessed at: https://energypost.eu/how-to-ramp-up-hydrogen-under-the-new-repowereu-targets/#:~:text=Half%20of%20the%20targeted%20hydrogen,for%20just%2033%25%20of%20consumption. (2022).

[10] Port of Rotterdam. Cespa and the port of Rotterdam join up to create first green hydrogen corridor between the north and south of Europe. Accessed at: https://www.portofrotterdam.com/en/news-and-press-releases/cepsa-and-the-port-of-rotterdam-join-up-to-create-the-first-green-hydrogen (2022)

methanol production or facilitate new applications such as SkyNRG's Sustainable Aviation Fuel plant[11].

Pipelines and a European Hydrogen Backbone

Existing electrical infrastructure is not thought to be capable of transporting the additional energy expected from Europe's renewable expansion, whether that be on- or offshore[12]. Therefore, with EU countries also trying to reduce their reliance on natural gas following the Russian invasion of Ukraine, the ability of hydrogen to move renewable energy in molecular form whilst decarbonising the built environment is being widely explored.

Trial projects testing concepts and technology have already shown promise across Europe. In the UK, the HyDeploy project has been trialling 20% hydrogen mixed with natural gas on Keele university's campus (30 faculty buildings and 100 domestic properties). A follow up project is already running where many homes will be connected to the mixed gas supply. Similarly, in Leeds, the H21 project has positively assessed the techno-economic viability of converting the gas grid in the North of England to 100% hydrogen and is now focused on shaping the necessary policy and safety codes to enable a widespread deployment of dedicated and blended hydrogen pipelines. The UK's Energy Networks Association has published a hydrogen blending delivery plan to ensure grid infrastructure is ready to deliver 20% hydrogen by 2023. However, the department of Business, Energy and Industrial Strategy (BEIS), has said blending will only play a 'limited and temporary' role[13] as the UK favours more decarbonising measures and the deployment of hydrogen into more lucrative markets.

The Netherlands have taken a stronger stance on transitioning the use of natural gas for heating. No new built houses are allowed to be connected to the natural gas network. New renewable solutions are being developed and trialled. In the HEAVENN project, a 100% hydrogen trial is taking place in a community in Hoogeveen in which newly built housing will be connected to a hydrogen network fed by locally sourced, road delivered hydrogen. This is a first step which will be followed by further local production and interconnection with new hydrogen pipeline networks, such as national systems or the European Hydrogen Backbone.

[11] SKYNRG. SKYNRG DELFZIJL (DSL-01). Accessed at: https://skynrg.com/producing-saf/skynrgs-production-facility-in-the-netherlands/ (2022).
[12] Energy Engineers. Identification of Potential Synergy Locations for Energy Infrastructure and Ten-T corridors (2019).
[13] Offshore Technology. Hydrogen Blending to play only "limited and temporary" role in UK gas grid. Accessed at: https://www.offshore-technology.com/news/hydrogen-blending-to-play-only-limited-and-temporary-role-in-uk-gas-grid/ (2022).

In mainland Europe, European gas Transmission Systems Operators (TSOs) came together in July 2020 to produce a vision document for the European gas sector to tackle its role in the energy transition – The European Hydrogen Backbone (EHB). The document set out how hydrogen can enable a reduction in emissions throughout Europe by offsetting the use of natural gas whilst maintaining a similar framework to what is used today. The plans utilise a mixture of refurbished natural gas and new dedicated hydrogen pipelines to deliver a pan-European hydrogen transmission and distribution grid focused on linking production hubs to demand centres (e.g. industrial clusters). This plan has been updated several times throughout the past two years, most recently following the Russian invasion of Ukraine and release of the Fit-for-55 and REPowerEU packages and now features a total of 28 countries. It is expected that by 2040, the continental network, which will cost between €80 – €143 billion, will enable an annual demand of at least 1,640 TWh to be transferred across a potential 53,000 km of pipelines[14].

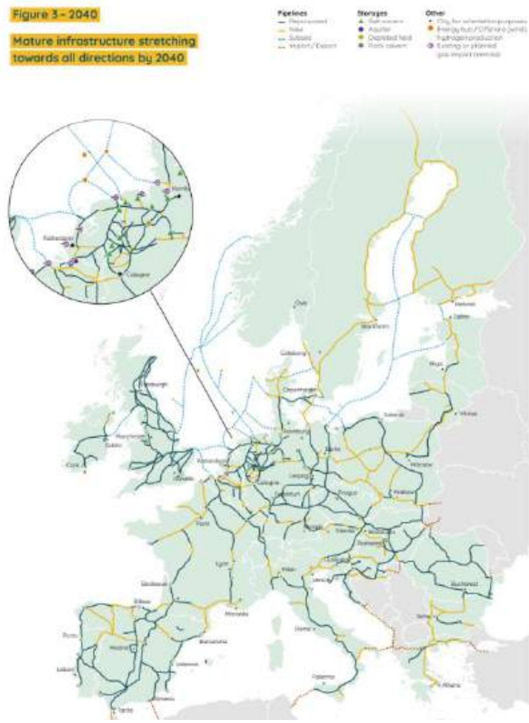

Figure 5*: 2040 European Hydrogen Backbone infrastructure* - EHB

Whilst this plan focuses primarily on the distribution of hydrogen across the continent for industrial use, its implementation will have a knock-on effect for the use of hydrogen within national systems too. Further linkages of European infrastructure, to supporting national infrastructure, such as Gasunie's hydrogen ring for the Netherlands[15], will enable the connection of European hydrogen flows, to regional use-cases without the need for large storage systems in urban areas. Transfer of hydrogen via pipeline, if done at 97-98% purity like Gasunie's ring, will require further purification for use in fuel cell applications such as mobility, but not for industrial and heating purposes and therefore can both directly and indirectly aid decarbonisation of hard-to-abate areas, particularly mitigating natural gas usage in the built environment.

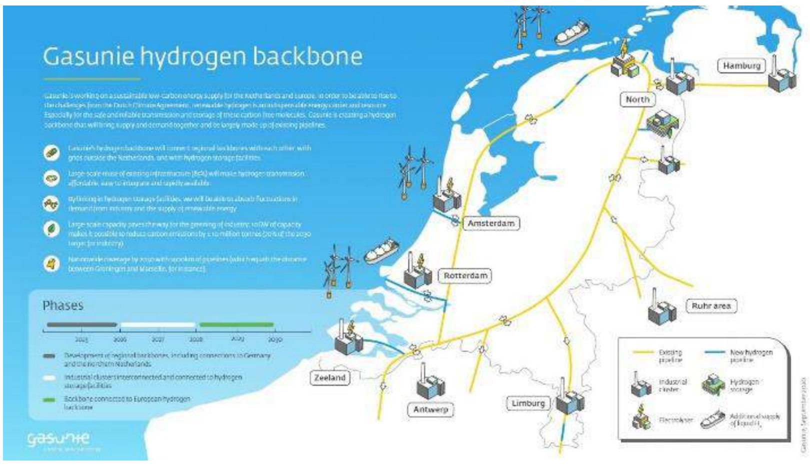

Figure 6*: Gasunie's hydrogen ring* - Gasunie

[14] EHB. European Hydrogen Backbone. (2022).
[15] Gasunie. Hydrogen Network Netherlands. Accessed at: https://www.gasunie.nl/en/projects/hydrogen-network-netherlands (2022).

Within HEAVENN, Gasunie's TSO2020 work to trial the viability of large-scale long-term hydrogen storage within caverns is being expanded.

Recognising the importance of the widespread hydrogen infrastructure, the EC are also investigating how hydrogen can also enable long-term energy storage in the wake of dwindling natural gas supplies. Gas Infrastructure Europe (GIE), an independent association dedicated to finding and regulating the best market solutions for the European gas sector, have similarly assessed the overall potential of underground gas storage within the European hydrogen system. GIE estimated a need for 70 TWh by 2030, and 450 TWh by 2050[16] of storage to realise the EHB's plans, figures that have likely increased following the EHB's update in April 2022. Gasunie's participation in HEAVENN is furthering the European knowledge by trialling underground hydrogen storage within a cavern as part of the project.

TEN-T Corridors

Mobility is expected to be an area of major hydrogen demand in the coming years. Currently, transport is the second largest emitter of CO_2 within the EU, only behind energy supply, contributing 945.8 million metric tonnes equivalents of CO2 to the continent's emissions (2018[17]) – not including international shipping and aviation emissions. It is likely that a large proportion of the passenger car market will switch to battery electric vehicles, given the technology's recent range advancements and its overwhelming market share of new vehicles. However, when it comes to heavy-duty vehicles hydrogen and Fuel Cell Electric Vehicles (FCEVs) have several advantages over Battery Electric Vehicles (BEVs). These include:

- **Advantageous refuelling profiles** that are similar to that of fossil fuel vehicles. Hydrogen trucks and buses can refuel in just 15 minutes, allowing greater operational flexibility.
- **Greater power-weight ratio.** FCEVs offer better performance in more intensive situations such as hilly terrains or when operating with extra amenities such as air conditioning.
- **Greater range** than battery electric vehicles, due to this ratio.
- **Less invasive and costly refuelling infrastructure.** Large scale fleet replacements with BEVs can incur expensive grid connections and cabling upgrades, whereas hydrogen vehicles can be refuelled in conventional forecourt environments.

[16] Gas Infrastructure Europe, Guidehouse. Picturing the value of underground storage to the European hydrogen system (2021).
[17] European Environment Agency. Greenhouse gas emissions by aggregated sector. Accessed at: https://www.eea.europa.eu/data-and-maps/daviz/ghg-emissions-by-aggregated-sector-5/#tab-dashboard-02 (2019)

Current projections, announced by the EU transport commissioner Adina Vălean, estimate 17% of new trucks in 2030 to run on hydrogen – roughly 60,000 units[18]. However, to realise the emission savings via the deployment of these vehicles, a simultaneous rollout of refuelling infrastructure will also be required. The European Commission's Alternative Fuels Infrastructure Regulation (AFIR) will see Hydrogen Refuelling Stations (HRSs) deployed along the TEN-T core network at a maximum spacing of 100 – 200km. These stations must have suitable capabilities to dispense 2,000 kg of hydrogen per day, and thus will be amply sized for fleet operators and large vehicles. Initially, many of these stations will be serviced by locally produced, trailered hydrogen but as throughput volumes increase trailers will be considered an inefficient supply method. Instead, as the European hydrogen sector grows, HRSs are likely to intersect with hydrogen pipelines, and thus could receive hydrogen directly from a European-wide hydrogen distribution network, with only compression and 'final km' transfer of hydrogen to the station required. Or, these HRSs could be serviced by liquid hydrogen (LHY), which due to its superior energy density in comparison to gaseous hydrogen, could not only distribute greater volumes of hydrogen per trailer, but also result in smaller station footprints as less storage space is required. Thus, as FCEV deployment increases, LHY could become the preferred storage medium for large-throughput stations by outsizing the possibilities of its gaseous analogue. A number of companies are already investing heavily in on board LHY technology, such as Daimler, who are developing heavy-duty vehicles to run on LHY.

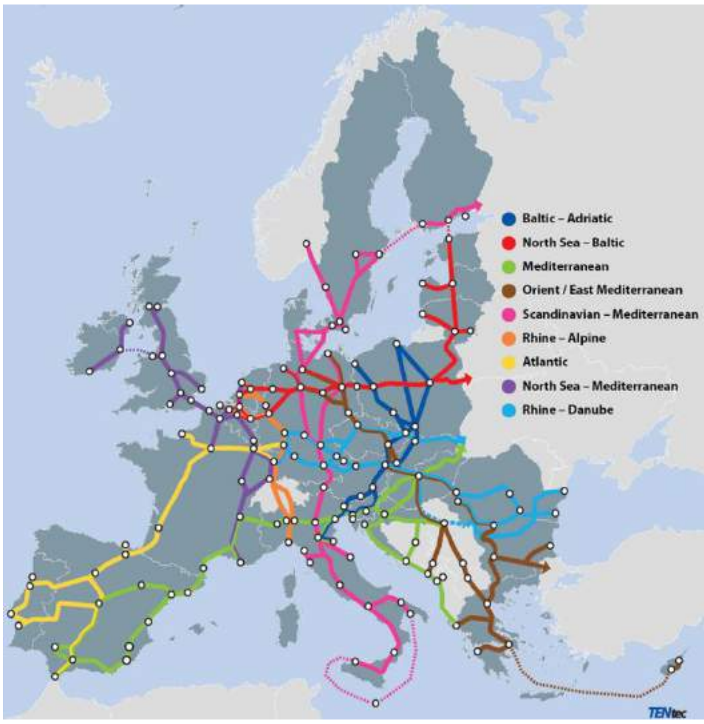

Figure 7*: Map of Europe's TEN-T corridors* - European Commission

Whatever the technology, great volumes of hydrogen will be required to service this ever-growing hydrogen refuelling network. The transport sector, like industry and heating, will need to secure their supply by engaging with overseas hydrogen supply value chains. Therefore, working together, industry, heating, and mobility will synergistically develop a European hydrogen market by providing the initial demand, framework, and infrastructure to foster a hydrogen economy.

Barriers to cross-border collaboration

However, before a continent-wide hydrogen economy is achieved, there are several barriers which must first be overcome. The H2LinkRegions project[19] has investigated the potential for cross-border hydrogen co-operation on between the Northeast of Netherlands and Northwest of Germany. This Interreg funded project determined that, although there are 218 hydrogen-interested companies and organisations based in the area, there were just three projects focused on cross-border cooperation. Although most were optimistic that cross-border hydrogen activities hold significant

[18] EURACTIV. 17% of new trucks in 2030 will run on hydrogen, EU believes Accessed at: https://www.euractiv.com/section/energy/news/17-of-new-trucks-in-2030-will-run-on-hydrogen-eu-believes/ (2022).

[19] New Energy Coalition, OLEC. Potential for Cross-Border Cooperation between the Northeast of the Netherlands and the Northwest of Germany in the field of Hydrogen as an Energy Carrier. (2020).

potential, the difference in regulatory frameworks, action strategies, and financing issues between regions and countries meant that working with foreign companies was too challenging. National hydrogen strategies, in their current form, risk creating regionally, or nationally concentrated hydrogen markets due to incongruous cross-border regulatory and competitive approaches. This is likely to continue without a concerted effort from policy makers to avoid monopolies, dominant positions, and preferential trading conditions of certain member states[20]. So far, the EU has taken a leading role in the technical and commercial development of the hydrogen sector through funding opportunities and public-private partnerships, but to ensure the sector's progression to a pan-European industry, it must widen its role in policy development too, and quickly. Policies should focus on a whole-systems approach, providing opportunities for international corporations, financial institutions, OEMs, and local SMEs to combine the necessary scale, knowledge, and innovation into a collaborative European hydrogen sector.

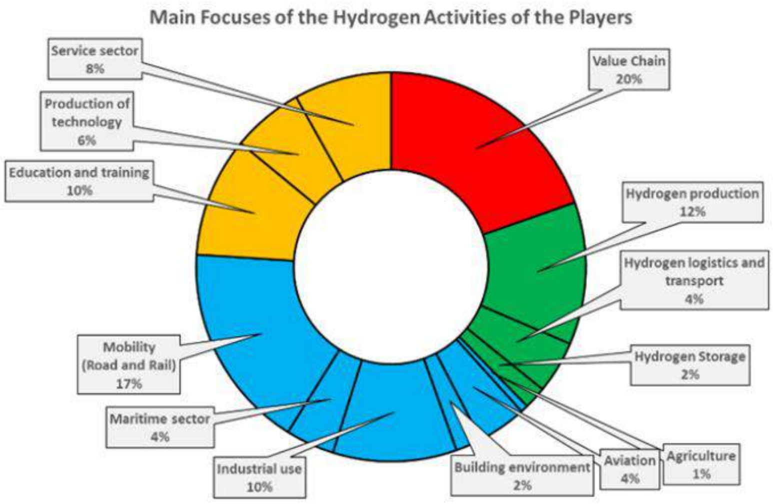

Figure 8*: The main focuses of the players in the region (Groningen, Drenthe and Niedersachen) shows there isn't a lack of expertise* – H2LinkRegions

In order to subvert some of these issues and develop a European hydrogen economy, the EU is seeking to join and build on national hydrogen strategies in the form of IPCEI projects. IPCEIs – **Important Projects of Common European Interest** – are a state aid arrangement mechanism created by the European Commission, with the objective of supporting large scale infrastructure projects that involve multiple nations that follow these key goals:

- Contribution to EU objectives
- Positive spill over effects
- Co-financing project beneficiaries and national/regional authorities
- Must be a major innovative nature of important added value*
- First industrial deployment of new innovative products*

**For Research, Development, and implementation (R&D&I) projects*

IPCEI projects are designed to reduce the difficulty plaguing the deployment of new large-scale infrastructure. Significant investment has been made available through this initiative to kickstart the hydrogen economy and enable cost-competitive low-carbon hydrogen prices. Several countries have already pre-approved a number viable IPCEI projects within their borders, such as Germany who

[20] Machado, Flynn, Williamson. The national shaping of Europe's emerging hydrogen strategies: Cooperative or competitive hydrogen politics? (2022).

currently have over 60 domestic IPCEI projects. However, to be eligible for funding, projects must join together, across borders, to form ‘waves’ dedicated to tackling challenges in key sectors – such as transport or heating. Through this process, we may see aligning of member states’ hydrogen policies as they converge and work together to obtain funding. In the following section, the hydrogen policies of three proximal nations to the HEAVENN region – Netherlands, Germany, and the UK – will be discussed to understand the differences in domestic hydrogen drivers, policy, and activities.

Hydrogen Production

Currently, the majority of global hydrogen is still produced using carbon-intensive methods, most commonly in a process called Steam-Methane Reformation ('grey'). During this process, methane (natural gas) is reacted with oxygen to produce hydrogen, which is captured, and CO_2, which is released directly into the atmosphere. The technology associated with Steam Methane Reforming is extremely mature and has been used for decades to produce large volumes of hydrogen at low cost, typically historically just €1 – 1.50/kg_{H2}. These systems are often directly connected to the chemical clusters and oil refineries they serve where hydrogen is used as a key building block for many products. However, despite its positives, grey hydrogen production is extremely emitting (roughly 10 kg_{CO2} for every 1 kg_{H2}). The goal of European economies is to move away from the use of grey hydrogen to less emitting variations, particularly for industrial processes. The two-leading low-carbon production pathways are 'blue' and 'green' hydrogen.

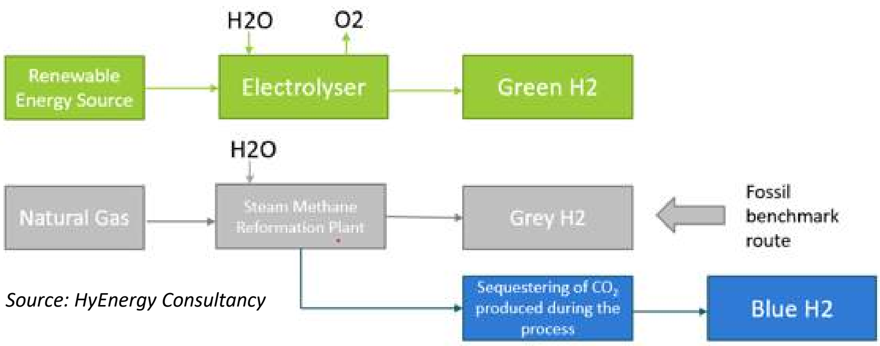

Figure 9*: The three principal hydrogen production pathways - green, blue and grey*

Blue hydrogen production features all the same technologies as grey hydrogen production with the addition of Carbon Capture Utilisation and Storage (CCUS) technologies to reduce the amount of CO_2 directly released into the atmosphere by around 80-95%. This option is being strongly considered by nations with CO_2 sequestration locations, such as those bordering the North Sea, but is seen by most to be a transitional option until less emitting methods are sufficiently mature. However, the energy price crisis, as well as the Russian invasion of Ukraine, have reduced focus on both blue and grey hydrogen production due to their dependency on natural gas feedstocks.

Green – utilises a technology called electrolysis to produce hydrogen from just water and renewable electricity, therefore having no associated carbon emissions. Green hydrogen technologies have been receiving great amounts of interest over the past five-years and, as such, are being fast tracked to maturity through public funding, from the EU and national governments alike. Although currently there is just 0.3 GW of installed electrolysis capacity, the EU plans to reach 6 GW by 2024, rising to a 40 GW by the end of the decade and be a leading centre for the manufacture of electrolysis technologies too.

Area	Applications	Relevance of application (hydrogen demand)	High deployment potential
Refineries	Naphtha	In refineries hydrogen is used for hydrocracking, hydrotreating and hydroformylation to produce gasoline, diesel, kerosene, naphtha and light heating oil.	Refineries already use hydrogen today, therefore no additional deployment is needed.
	Gasoline		
	Kerosene		
	Diesel		
	Light heating oil		
Base chemicals	Methanol	Hydrogen can be used as a base material for the production of chemical substances.	Manufacturers can produce basic chemicals synthetically with hydrogen in order to reduce CO2 emissions.
	Ammonia		
Steel production	High-tensile steel	New production procedures for steel are emerging that require great amounts of hydrogen.	Steel producers need to get their CO2 emissions down and are therefore urged, to introduce cleaner production methods.
	Crude steel (furnace with H2 injection & direct reduction)		
Public services	Solo buses	Hydrogen is an ideal fuel for larger vehicles that operate in urban areas, especially when there is a lot of stop and go traffic going on.	Fuel cell technology is mature and proven, public fleet operators have to decrease local CO2 and other harmful emissions from conventional drive trains and fuel cells deliver a possible solution.
	Articulated buses		
	Garbage trucks		
Logistics	Light	Road transport of goods consumes a large amount of energy which can be met by hydrogen due to its high energy density compared to batteries.	For heavy duty or long distance transport, hydrogen is a suitable option towards zero emission.
	Heavy		

Figure 10*: A summary of key industrial and mobility hydrogen technologies that are likely to see deployment*

It is clear from recent regional, national, and international legislation that hydrogen will play a key role in transitioning global economies away from polluting fossil fuels. Low-carbon hydrogen will not only replace existing fossil-fuel derived hydrogen in industry, but also growing demand from transport, the built environment (etc.). The sector drivers discussed in the previous section will be a critical instrument to geographically broaden the EU's hydrogen sector from its industrial base in the Netherlands and Germany, to a continent-wide emission saving sector. Currently, however, regions are being split into two distinct categories:

Energy Exporters – Locations with considerable renewable potential that exceeds domestic demand.

Energy Demand Centres – locations which have a larger demand than can be satisfied through locally produced low-carbon energy sources.

In an ideal world, large hydrogen demand centres would be situated right next to key production locations to minimise the necessity for storage and distribution mechanisms; providing the lowest Levelised Cost Of Hydrogen (LCOH). In practice, however, that is not the case. Locations and makeup of hydrogen production and demand varies greatly. The EU overall is a large energy demand centre, importing 55.6% of its energy needs (2021[21]), and has one of the largest global hydrogen demands due to its industrial hydrogen applications. The best energy export locations, however, are based in areas with reliable high-capacity factor renewable resources, such as the Middle East, northern Africa, South America, and Oceania. Therefore, recognising this mismatch, EU countries have been actively investigating partnerships with ideal renewable locations to secure greater amounts of low-carbon energy which they can decarbonise and grow their domestic economies. In the following section,

HYDROGEN COLOURS AND TYPOLOGIES — CIC energiGUNE

COLOUR	SOURCE	PRODUCTION TECHNOLOGY	DIRECT CO_2 IMPACT
H_2 Green	Renewable Electricity and Water	Electrolysis	No
H_2 Grey	Natural Gas	Methane reforming	Yes
H_2 Black	Black Coal	Gasification	Yes
H_2 Brown	Brown Coal	Gasification	Yes
H_2 Pink	Nuclear Electricity and Aater	Electrolysis	No
H_2 Blue	Natural Gas or Coal	Methane reforming	No *captured and stored
H_2 Turquoise	Natural Gas	Pyrolysis	Yes
H_2 Yellow	Solar Power and Water	Electrolysis	No
H_2 Orange	Solar Irradiance and Water	Photolysis	No
H_2 Red	Nuclear Heat and Water	Thermolysis	No
H_2 Purple	Nuclear Electricity, Heat and Water	Thermolysis and Electrolysis	No

Figure 11*: The rainbow of hydrogen production - CIC energiGUNE*

[21] Eurostat. EU energy mix and import dependency. Accessed at: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=EU_energy_mix_and_import_dependency#Energy_mix_and_import_dependency (2022).

the cost of hydrogen production within the HEAVENN region will be contrasted with the cost of international production to understand the competitiveness of locally produced green and blue hydrogen within the rapidly developing global market.

The cost of hydrogen – HEAVENN region production

Domestic low-carbon hydrogen production will occur in two distinct pathways – green and blue hydrogen production. With the current €60/t_{CO2} tax that is present in the EU, blue hydrogen production is already cost-competitive with grey hydrogen pathways, with historic and recent production costs of just above €2/kg_{H2} each. However, both these pathways are incredibly dependent on the cost of natural gas and so recently, due to the energy crisis and the Ukraine-Russia conflict, the price of blue and grey hydrogen has sky-rocketed to as much as triple its previous cost – €6.55/kg_{Grey} and €6.21/kg_{Blue} in October 2021[22]. Previously it had been predicted that blue hydrogen prices in Europe could reach ~€1.60 – €1.80/kg_{H2} by 2030 with simultaneous increases in scale, carbon capture rates and carbon taxes – although in the current energy landscape, and increased decarbonisation pressure, this now seems unlikely.

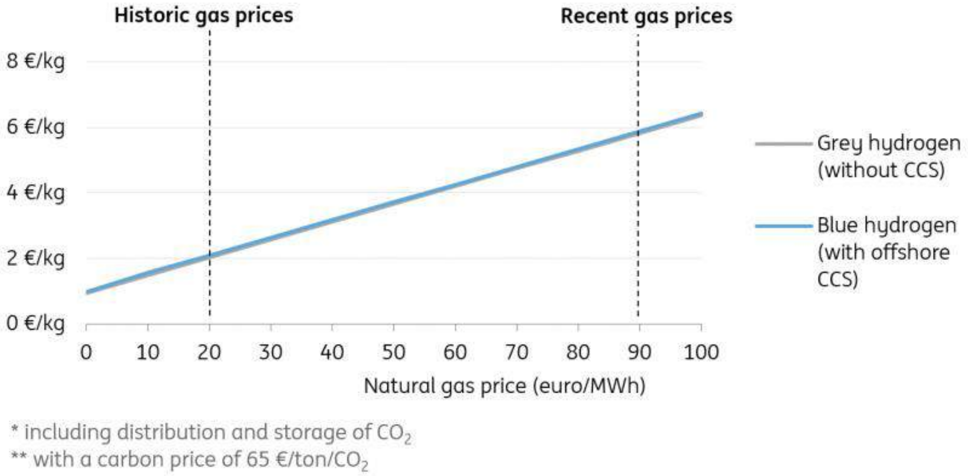

Figure 12*: The cost of grey and blue hydrogen are highly dependent on natural gas prices* – ING Research

Green hydrogen production, on the other hand, is not dependent on the price of natural gas and whilst blue and grey hydrogen prices have tripled, green hydrogen is only becoming more cost-competitive in Europe at €4.00-4.15/kg_{Green} (assuming PPA agreements of €50/MWh)[22]. Within the HEAVENN region, the cost of green hydrogen production is extremely reliant on the development of large-scale renewables, particularly offshore wind farms, to ensure a reliable stream of low-cost energy to power electrolysis equipment. In Northern Europe, where energy prices are higher than places such as the Middle East, northern Africa, or Oceania, a realistic price of $2.50/kg is expected to be achieved by 2030, according to the Hydrogen Council. However, with increased pressure to secure the EU's energy supply, the EC have placed an emphasis on the role of hydrogen in their energy system going forward – expanding production and import targets with desired costs to be as low as €1.80/kg by 2030 (~$2/kg). The Netherlands is taking a leading role to helping achieve these goals, both through its early adopter position, and its national subsidies which offer €1.43bn per GW of electrolysis capacity committed as part of a new €35bn climate and transition fund designed to accelerate Dutch decarbonisation.

HEAVENN Region	**2022**	**2030**	**2050**
Historic Blue Hydrogen	2.00	1.60 - 1.80	1>

[22] RECHARGENews. 'Green Hydrogen now cheaper to produce than grey H2 across Europe due to high fossil gas prices'. Accessed at: https://www.rechargenews.com/energy-transition/green-hydrogen-now-cheaper-to-produce-than-grey-h2-across-europe-due-to-high-fossil-gas-prices/2-1-1098104 (2021).

Production cost (€/kg$_{H2}$)			
Recent Blue Hydrogen production cost (€/kg$_{H2}$)**	5.00 – 6.50	2.00 – 2.60	2.95 – 3.85
Green Hydrogen Production cost (€/kg$_{H2}$)*	3.50 - 6.00	2.50 – 5.00	1.50 - 3

Table 1*: *Hydrogen production costs relating to production within the HEAVENN region - Figures included have been produced via a literature review and the author's market knowledge, with expected power costs of €50/MWh in 2022, €38/MWh in 2030 and €28/MWh in 2050 all taken from estimates from IRENA's Future of Wind report (2019). ** Recent blue hydrogen production costs have been produced using figures from Deloitte's oil and gas price forecast (September 2022).*

The cost of hydrogen – International value chains

Ports based within the HEAVENN region will act as energy hubs – key onshoring locations for domestic renewable energy production and import terminals for energy produced from other countries in the form of hydrogen, ammonia, and other synthetic fuels.

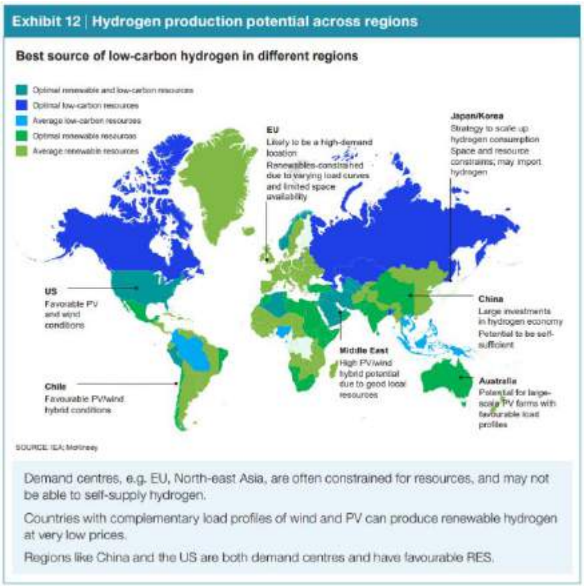

Figure 13*: Optimal hydrogen production locations* – Hydrogen Council

The most likely production pathways of internationally distributed hydrogen will be by renewable energy coupled with electrolysis. Any momentum surrounding the development of blue hydrogen international value chains has been dampened by the ongoing energy crisis and Russian invasion of Ukraine. This this pathway is only being strongly considered in locations with advantageous geographic properties, such as large-scale CO_2 sequestration opportunities as seen around the North Sea, or access to large amounts of natural gas, such as the Middle East. Therefore, for this analysis the import of blue hydrogen will not be considered.

CAPEX costs of electrolysis deployments are admittedly large, however when offset over the lifetime of deployments its impact on every kilogram of hydrogen produced is low. This amortised cost is also expected to be reduced further from economies-of-scale as so-called 'giga-factories' come online. Instead, a large proportion of the cost to produce hydrogen via electrolysis comes from the cost of electricity to run the system with the goal of $20/MWh cost of energy seen as the target which will unlock cheap and reliable green hydrogen production[23]. Nel Hydrogen has stated that with this idealised electricity price, production costs of $1.50/kg could be achieved as soon as 2025[24], but this is unlikely in Europe due to comparatively worse wind and solar capacity factors. For example, estimates published as part of the European Commission's hydrogen strategy in July 2020 stated production costs were between $3-6.55/kg. Therefore, these pathways have become popular is archetypical renewable geographies such as the Middle East, Africa, and Oceania where production costs of $1.50/kg could be achieved by the end of the decade.

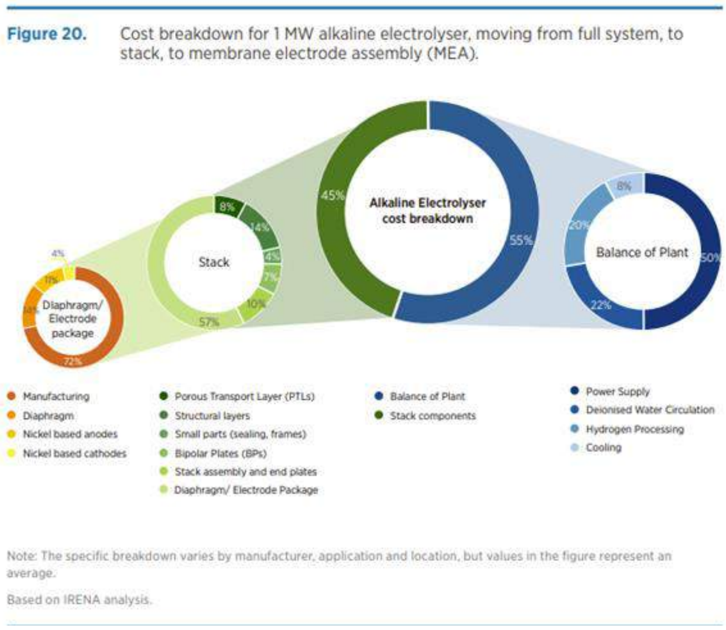

Figure 14*: Breakdown of electrolysis costs* - IRENA

Further influences, such as the US' Inflation Reduction Act (IRA), could also increase the share of internationally produced hydrogen within Europe's market. The IRA, which offers a generous subsidy of $3/kg green hydrogen producers, is luring suppliers to deploy systems in the US as a result of improved business models. In the long-term this could lead to decreased deployment rates and increased production costs in Europe.

Export Locations	**2022**	**2030**	**2050**
Green Hydrogen Production cost (€/kg$_{H2}$)	3.25 - 4.50	2.00 - 2.75	1.00 - 1.25

Table 2*: Data taken from PwC research on the cost of worldwide hydrogen production from archetypical export locations such as Australia, Saudi Arabia, Chile, Morocco.*

Transformation and Transmission

Hydrogen, unlike conventionally traded fuels such as diesel and kerosene, requires conversion into a transfer molecule, with far superior storage qualities, to make large-scale international distribution financially viable. The hydrogen sector is investigating Liquid Organic Hydrogen Carriers (LOHCs), liquid hydrogen (LHY), and ammonia for this purpose.

LOHCs, such as naphthalene (7.2 wt%H_2), toluene (6.5 wt%H_2), or dibenzyltoluenes (6.2 wt%H_2)[25], can all behave as a stable storage medium for the transportation of hydrogen. Within established

[23] IRENA. MAKING THE BREAKTHROUGH Green hydrogen policies and technology costs. (2021).
[24] S&P Global Market Intelligence. Electrolyzer-maker Nel targets green hydrogen at $1.50/kg. Accessed at: https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/electrolyzer-maker-nel-targets-green-hydrogen-at-1-50-kg-62216178 (2021).
[25] Solovechik. Bridging Renewable Electricity with Transportation Fuels. (2015)

sectors, LOHCs are being considered to move high volumes of hydrogen over long distances (>1500km). These frequently feature point-to-point delivery mechanisms, or extreme weather conditions where conventional hydrogen apparatus would not function effectively, as demonstrated in the HySTOC project in Finland. LOHCs require reconversion to separate hydrogen from its carrier molecule, which is then recycled for further use. This process, its associated cost and energy requirements, are highly dependent on the carrier molecule, hydrogen end-use and necessary purity. These technologies, however, are still at an early stage in their development cycle and require further development to adequately penetrate the market.

To produce LHY from gaseous hydrogen, an extra step is required – liquefaction. During this process, hydrogen is cooled to below -250 ^{0}C, at which point it changes phase and then is typically stored in large cryogenic containers. Whilst this process is relatively new to the European market, the US has been utilising liquefaction for over two decades to maximise the volume of hydrogen that can be distributed along lengthy transportation corridors. It is worth noting that this process is extremely costly and energy intensive – requiring roughly 30% of the total energy delivered to operate current plant sizes[26]. Recent sector developments have seen shipping LHY investigated as part of a demonstration project between Australia and Japan. LHY shipping allows a significantly smaller scale of hydrogen to be transported when compared to Ammonia or LOHC shipping and therefore will likely only be suitable for end-use applications that require pure LHY.

Ammonia (17.7 wt%H_2[27]) is the sector's current front runner as can be seen in the NEOM project where Air Products, with Saudi Arabian governmental backing, will deploy a 4GW, $5bn green hydrogen plant capable of producing 650 tonnes per day. The majority of this hydrogen will be converted to ammonia and distributed around the world via ship. This transportation is likely to be initialised in 2025, with large-scale deployment realised between 2030-2035. Shipping ammonia is a readily used process within the chemicals industry already, particularly for fertiliser production, with tankers capable of carrying in excess of 60,000 Mt_{NH3}. Therefore, this is seen as a cheaper, safer, and easier option to quickly implement large-scale cross-border distribution of green hydrogen.

Transformation process	2022	2030	2050
Hydrogen to Ammonia conversion cost (€/kg_{H2})	1.02	0.95*	0.90
Ammonia to Hydrogen conversion cost (€/kg_{H2})	0.85 – 1.13	0.81 – 1.08*	0.77 – 1.03
Hydrogen to Liquid Hydrogen conversion cost (€/kg_{H2})	1.03 – 2.20	0.99 – 1.69*	0.90 – 1.10
Shipping ammonia (£/kg_{H2} per 1000km) [42] [28]	0.027	0.02*	0.02
Shipping Liquid Hydrogen (£/kg_{H2} per 1000km) [42]	0.094	0.061	0.04 – 0.05

Table 3*: Costs associated with hydrogen transformation processes and shipping transformed molecules – costs have been produced via literature review and author's market knowledge.*

[26] Office of Energy Efficiency & Renewable Energy. Liquid Hydrogen Delivery. Accessed at: https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery#:~:text=Liquid%20Tankers,-Currently%2C%20for%20longer&text=Over%20long%20distances%2C%20trucking%20liquid,for%20boil%2Doff%20during%20delivery. (2022).

[27] Andresson and Grönkvist. Large-scale storage of hydrogen (2019).

[28] Al-Breiki, Bicer. Comparative cost assessment of sustainable energy carriers produced from natural gas accounting for boil-off gas and social cost of carbon. (2020).

Distribution

Trucking hydrogen is the most common form of hydrogen distribution currently used in the sector, with the majority of these journeys being carried out by gaseous tube trailers – a regularly used industrial solution capable of carrying somewhere between 500 - 1,000 kg, rising to 1,200 kg in payload some innovative cases. It is becoming more common to transport hydrogen by road in its liquid form via the use of liquid tankers due to the increased payload potential – 2,500 – 4,000 kg. Liquid hydrogen tankers have a lower cost of transportation per kg_{H2} but increased CAPEX and require a greater operational expertise due to safety requirements as the hydrogen must be stored under great pressures at <-250 ^{0}C. Therefore, for this reason, it's likely that short and relatively small deliveries of hydrogen are likely to remain using tube trailers, whilst larger deliveries will be able to make better use of the increased payload size to make liquid hydrogen deliveries economical.

A 2021 study[29] compared the potential to service Germany's predicted 2050 hydrogen mobility stations via different trucking methods (gaseous, liquid and LOHC). Within this scenario, 15 large-scale production sites, based in the North of the country, were theorised to service a total of 9683 hydrogen refuelling stations across Germany. When utilising gaseous tube trailers (carrying an effective payload of 1,100kg) it was found that 1,875 trucks would be required effectively transporting hydrogen at a cost of €2.69/kg for an average 417km (€0.0064/kg_{H2}/km) journey. Whereas, liquid hydrogen, due to an increased payload of 4,300kg, only required 419 trucks, transporting at just €0.73/kg_{H2} on average (0.0017/kg_{H2}/km). This analysis concluded that for short source-sink distances (<130km) gaseous hydrogen would be the most cost-effective form of transportation, with longer distances being more suited to liquid transportation.

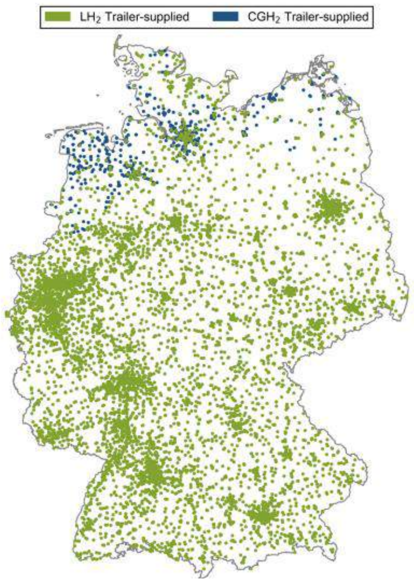

Figure 15*: Optimised distribution methods for hydrogen refuelling stations* - Hydrogen Road Transport Analysis in the Energy System

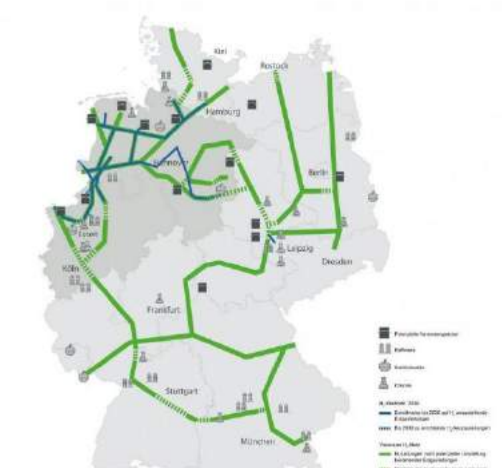

Figure 16*: Germany's visionary hydrogen grid* - H2 Startnetz

The paper, however, did not take into account the potential to refill tube trailers from a decentralised, European hydrogen pipeline network. With such a network, gaseous tube trailers could refill from multiple locations around Germany – allowing for more short delivery route options by increasing the number of hydrogen accessible locations across the breadth of the country, not just in the north. This could lead to a lower number of required vehicles, smaller round-trip journeys, and a lower distribution price of hydrogen. Therefore, for countries with access to decentralised source of hydrogen filling – i.e. a pipeline network – it is likely that compressed gas deliveries will remain the optimum delivery method for proximal customers. For

[29] Reuss, Dimos, Léon, Grube, Robinius, Stolten. Hydrogen Road Transport Analysis in the Energy System: A Case Study for Germany through 2050. (2021).

the HEAVENN region, which will look to serve external markets via export, it is likely that a mixture of both gaseous and liquid deliveries will be the most ideal solution depending on customer location and desired format (e.g. phase, format, scale).

Whereas pipelines offer a super-efficient form of gaseous hydrogen transportation, connecting production directly to customers with much higher throughput. However, they come with a very high CAPEX cost. Installing new dedicated pipelines could cost somewhere between €1.4 – €3.4m/km, not to mention the millions of euros of compression that would also be required. However, this cost can be significantly reduced through the use of repurposed natural gas pipelines for hydrogen at just €0.2 – €0.6m/km. The prevalence of natural gas infrastructure in Europe means that the hydrogen backbone plan could leverage ~60% repurposed pipelines, leading to a levelized cost of transportation of just €0.11-€0.21 per 1000km per kg_{H2}[30]. These costs associated with a European-wide network of pipelines and so for private pipelines, connecting industrial users direct with supply sites, costs may vary – although the increased cost that could be incurred is most likely justified for security of supply reasons.

Distribution process	2022 Cost (€/kg_{H2})	2030 Cost (€/kg_{H2})	2050 Cost (€/kg_{H2})
Dedicated pipeline (€/kg_{H2} per 1000km) – LCOT	0.18 - 0.81	0.11 – 0.60	0.11 - 0.21
Gaseous hydrogen tube trailers (€/kg_{H2} per km)	0.016 - 0.018	0.01 - 0.014	0.0064 – 0.01
Liquid hydrogen tankers (€/kg_{H2} per km)	-	0.0025 – 0.0075	0.0017 – 0.0035

Table 4*: Costs associated with hydrogen distribution processes and shipping transformed molecules – costs have been produced via literature review and author's market knowledge.*

[30] EHB. European Hydrogen Backbone. (2022).

Regional Neighbours – beyond the HEAVENN region in the Netherlands, Germany, and the UK

In order to quantify the export potential of hydrogen produced and processed within the HEAVENN region, the hydrogen landscape of its neighbours must be assessed to understand their desire to import hydrogen. Within this section, the respective hydrogen sectors, markets, and policy of Germany, the UK, and the rest of the Netherlands excluding the HEAVENN region, will be assessed.

Northern Netherlands

Following local pressure to implement climate action measures, arising from subsidence and earthquakes triggered by rapid extraction of Natural Gas (NG) in the northern provinces, the Dutch government has been instrumental in advancing low-carbon hydrogen policy and activities in the EU. The country, which has extensive experience within the natural gas sector due to assets such as the Groningen gas field - the largest NG field in Europe and the tenth largest in the world – understands the need to change their energy landscape. Hydrogen, and other zero-emission technologies, represent the perfect opportunity to transition jobs away from fossil-fuel industries to a greener future whilst reducing CO_2 emissions. This has led to the following targets released as part of the Government's National Climate Agreement[31] and Strategy on Hydrogen[32]:

- Reduction of Netherlands Greenhouse Gas (GHG) emissions by 49% by 2030, rising to 95% by 2050, compared to 1990 base year
- Ban on new NG connections to homes
- Reduce use of Groningen gas field. Further local earthquakes have led the government to double down on this position, announcing its intention to close the site by the end of 2024[33]
- Ban on sale of new CO_2 emitting passenger vehicles by 2030, and trucks by 2040.
- 50 Hydrogen refuelling stations by 2025 and 15,000 FCEVs, rising to 300,000 FCEVs by 2030
- 500 MW electrolysis capacity by 2025 increasing to 3-4 GW by 2030

Apart from the goals for passenger vehicles, which were developed when some time ago, scaling up the domestic zero-emission activities, especially for production, is considered essential by the Netherlands as they strive to be capable of meeting their own demand by 2050. Hydrogen will be 'indispensable' to helping the country achieve a 100% climate neutral economy by 2050 – playing a role in mobility, industry, and heating. However, the Netherlands also understands that there will be a vast demand for carbon-neutral hydrogen in the whole of north western Europe. Thus, the country is readily investigating the development of export opportunities from Netherlands to its surrounding neighbours which can bring added value back. These value chains will utilise critical infrastructure, such as Dutch ports, to make the Netherlands a cornerstone connection for the European energy sector.

Production – The Netherlands has a workforce that is already skilled in the production and handling of gases, particularly hydrogen. Local industry currently produces around 800,000 tonnes of hydrogen annually, primarily via grey production pathways – utilising 10% of the country's NG supply. Acknowledging this, the Dutch government has set out targets to increase the production and use of green hydrogen, via electrolysis, and blue hydrogen, via CCS. The latter is seen as a necessary transition tool to achieve net-zero until completely zero emission technologies are sufficiently mature – whilst making good use of the Netherland's access to geological storage sites

[31] The Hague. National Climate Agreement. (2019).
[32] Government of the Netherlands. Government Strategy on Hydrogen. (2020).
[33] Government of the Netherlands. Groningen gas field on the back burner in October. Accessed at: https://www.government.nl/latest/news/2022/06/20/groningen-gas-field-on-the-back-burner-in-october (2022).

on land and at sea. Although blue hydrogen projects have seen delays following rulings by the highest court in Netherlands due the nitrogen exemption targets[34]. The Dutch government are currently targeting 500MW of electrolysis capacity by 2025 through sector coupling opportunities with the available renewable resources, particularly offshore wind in the North Sea. To secure the country's supply, however, the Netherlands will likely have to import hydrogen due to the size of their demand.

Applications - As mentioned previously, The Netherlands will be focusing their efforts upon two very large carbon emitting and NG using sectors – industry and heating (42% of total energy supply was satisfied with NG in 2018[35]). Whilst electrification is an option for these areas, the opportunity to repurpose Netherland's widespread NG infrastructure can make hydrogen a viable and cost-effective option. Thus, the Dutch government has taken an active role in establishing European-wide hydrogen distribution infrastructure – the EHB - particularly positioning the Port of Rotterdam to continue its leading energy position for Europe within these plans. They are also actively investigating the development of a dedicated hydrogen network domestically, introducing hydrogen blending into existing NG infrastructure, and making use of geological storage locations for large-scale, long-term storage of hydrogen gas.

Mobility is also a key area of focus for The Netherlands. Initial targets were placed on the introduction of fuel cell electric passenger vehicles, with goals of 15,000 units deployed by 2025, ramping up dramatically to 300,000 by 2030. However, as Battery Electric Vehicles (BEV) have established a larger market share in this area, impetus has shifted to tackling medium- to heavy-duty applications. Therefore, new targets of 3,000 hydrogen HGVs on the road by 2025 instead have been introduced; utilising public fleets to drive demand from private manufacturers. Netherlands is now home to an ever-increasing number of manufacturers of these vehicles, including HYZON who have established their European base in the northern Netherlands following partnership with Holthausen. Strategic collaborations within European projects, such as H2 Trucks which will put 1,000 hydrogen-powered HGVs on the Netherlands/Belgium/Germany transport corridor by 2025, are also helping to accelerate the rollout of hydrogen HDVs. A €22m national fund to subsidise the roll-out of hydrogen refuelling infrastructure for trucks was recently announced in November 2022[36], with each station that wants to obtain funding needing to purchase around 20-25 hydrogen trucks to break the 'chicken and egg' issue currently exhibited in the sector.

Aside from road vehicles, marine vessels are being particularly targeted as well in The Netherlands, with a desired reduction of 40% CO_2 emissions produced by ports and maritime activities. Dutch inland shipping is an area of initiating interest and targets the lowest CO_2 emissions per tonne of transported cargo weight per km of any transport type. Within the HEAVENN project the MS Antonie will enter service as the first hydrogen powered bulk carrying cargo vessel in Europe.

The simultaneous development of national hydrogen policy, and the need to achieve net-zero will see hydrogen demand rise significantly out to 2050. Over the next decade, demand is expected to increase by 17% - equivalent to 141,000 tonnes/annum – building upon the existing industrial demand of 1.5 Mt/annum.

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[34] Argus. Dutch court ruling delays CCS, blue hydrogen projects. Accessed at: https://www.argusmedia.com/en/news/2387316-dutch-court-ruling-delays-ccs-blue-hydrogen-projects (2022).
[35] IEA. The Netherlands 2020 Energy Policy Review. (2020).
[36] Hydrogeninsight. Dutch government will subsidise hydrogen filling stations and trucks – together or not at all. Accessed at: https://www.hydrogeninsight.com/transport/-chicken-and-egg-situation-dutch-government-will-subsidise-hydrogen-filling-stations-and-trucks-together-or-not-at-all/2-1-1360288 (2022).

Germany

Germany is a leader in hydrogen production, consumption, and policy. Their national hydrogen strategy[37], which was released before even the EU's strategy, features collaboration between five German ministries and major legislation suggestions to develop a domestic low-carbon hydrogen sector. Germany's overall hydrogen demand, which is already one of the largest in the world, could more than double by 2030. To meet this scaling demand Germany prioritise coupling an increase renewable energy, particularly offshore technologies, with electrolysis to produce green hydrogen. Hydrogen will play a critical role in helping Germany achieve its 2050 climate targets, whilst adding value to the domestic economy by exporting expertise to foreign territories. Hydrogen will behave:

- As an energy source through the deployment of fuel cell applications
- As an energy storage mechanism for intermittent renewable energy which also helps to increasing energy efficiencies of renewable deployments by reducing curtailment and furthering sector coupling through balancing.
- As a base feedstock in chemical production whether that be alcohols or ammonia.
- As an enabler for the decarbonisation of Germany's NG network – once feasibility has been proved.

The national strategy focuses on the key 5 key geographic regions: Bremen, Hamburg, Mecklenburg-Western Pomerania, Lower Saxony and Schleswig Holstein. These regions feature strategically unique characteristics such as geological storage, ideal renewable resources, seaports, industry (etc.). Germany foresees its hydrogen demand increasing to between 90 – 110 TWh by 2030[38]. Germany has placed much of their focus on green hydrogen production pathways in order to maximise CO_2 savings by deploying a long-term 'ethical' approach. The latest German coalition has doubled down on this focus, following the Russian invasion of Ukraine. Fossil gas-based hydrogen (including blue) will not be included within their subsidy schemes[39], whilst green hydrogen ambitions have doubled from 5GW to 10 GW electrolysis capacity by 2030.

The government in Germany will focus on developing hydrogen hubs to initialise green hydrogen production and base demand around mobility and industry. Regionally, they are also progressing various hydrogen valley initiatives with a key focus in the north where connection with the northern Netherlands' HEAVENN region is being progressed.

Production - German industry currently consumes about 1.7 million tonnes, or 55TWh[40], of hydrogen per year. However, most of this hydrogen is produced from fossil-fuel derived pathways. To switch to 100% low-carbon alternatives, Germany will need to access international hydrogen value chains, as well as domestic opportunities, due to the scale of demand that is required.

Instead, the country *will* behave as a net consumer of green hydrogen. For instance, €2bn of Germany's €9bn national hydrogen strategy is earmarked for foreign investment, ringfenced to aid the development of overseas hydrogen sectors. This money has been invested into the H2Global mechanism – an initiative that aims to develop large-scale green hydrogen (as well as ammonia, methanol, chemicals and aviation fuel) production projects to export German technologies, import the hydrogen produced back to Germany, and accelerate the development of a global hydrogen economy. Germany has already started to establish partnerships as part of the H2Global programme

[37] Federal Ministry For Economic Affairs and Energy. The National Hydrogen Strategy. (2020).
[38] CSIS. Germany's Hydrogen Industrial Strategy. Accessed at: https://www.csis.org/analysis/germanys-hydrogen-industrial-strategy (2021).
[39] EURACTIV. German government disavows blue hydrogen. Accessed at: https://www.euractiv.com/section/energy/news/german-government-disavows-blue-hydrogen/ (2022).
[40] Mitsui & Co. Germany's National Hydrogen Strategy. Accessed at: https://www.mitsui.com/mgssi/en/report/detail/__icsFiles/afieldfile/2021/02/19/2012_fuhrmann_e.pdf (2020).

and is focusing a lot of their interest on renewables-rich locations, such as, for example, Namibia[41]. Namibia will receive up to €40m from Germany's stimulus package to accurately investigate and initialise their green hydrogen economy. Once established, long-term contracts for the hydrogen will be sold in Germany via annual auctions, with the Ministry of the Economy compensating the difference to the domestic sale price of hydrogen.

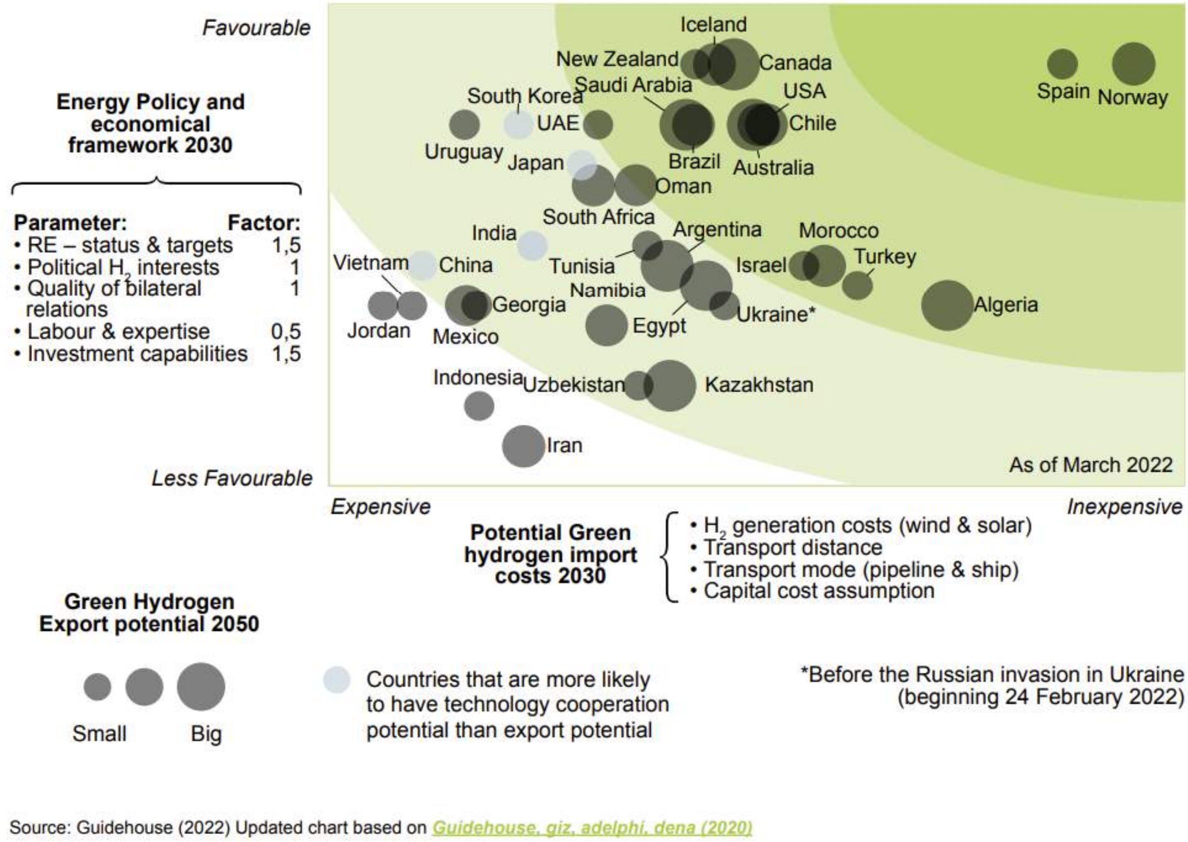

Figure 17: *International export opportunities with Germany* – Covering Germany's green hydrogen demand: Transport options for enabling imports (Guidehouse)

Germany also recognises it will require a large amount of imported green hydrogen if it is to realise a net-zero economy, as the country will not possess suitable capacity to satisfy its own demand. Therefore, a long-term plan to link Germany and Netherlands, and other nations, via hydrogen pipelines, is being investigated to provide increased access to hydrogen from foreign renewable rich and energy import locations. Strategic agreements, such as this, will be key to establishing global hydrogen trading routes and satisfying the current green hydrogen demand of Germany which is expected to be account for more than half of the combined hydrogen import demand of all European countries[42].

Applications – Germany's industrial base will dominate demand for hydrogen. The government does not want to disadvantage these critical consumers, instead making it simple and cost-effective to migrate their current production pathways to sustainable alternatives whilst utilising existing infrastructure, and protocols. The National Hydrogen Strategy features dedicated measures focused on furthering decarbonisation within the industrial sector, particularly steel and chemical

[41] RECHARGENews. Germany eyes world's cheapest green hydrogen from Namibia amid global 'race for best sites'. Accessed at: https://www.rechargenews.com/energy-transition/germany-eyes-worlds-cheapest-green-hydrogen-from-namibia-amid-global-race-for-best-sites/2-1-1057335 (2021).
[42] Guidehouse. Covering Germany's green hydrogen demand: Transport options for Enabling imports. (2022).

production. These include CAPEX funding for innovative solutions, such as hydrogen for high-temperature heat, and operational support for the implementation of green hydrogen feedstocks in process industry in the form of a Contracts for Difference (CfD) scheme.

Germany was an early mover in the establishment of hydrogen mobility infrastructure, as can be seen by their target for 100 HRSs by 2020. COVID-19 and supply chain related delays meant Germany did not achieve this target but currently has 95 with a further ten in various planning stages[43]. To support the rollout of hydrogen mobility, Germany's National Hydrogen Plan has provided extensive funding for zero-emission mobility incentives. These include:

- €3.6b to support green transport investments:
    - €2.1bn for the purchase of EVs and FCEVs – with 30,000 FCEVs expected by 2025
    - €0.9bn for the purchase of other utility vehicles with climate-friendly drive chains
    - €0.6bn for the purchase of zero-emission buses.

Heavy-duty road transport, trains, maritime, and aviation are all areas that Germany recognise that will all favour hydrogen and synfuels over electrification. However, before committing these applications to a strict decarbonisation pathway, Germany is investigating the necessary infrastructure, cross-border standards, and zero-emission taxing systems to foster successful transition.

United Kingdom

Despite leaving the EU, the UK have remained a signatory to the Paris Agreement and thus has similar, legally binding, climate goals to that of their continental neighbours. Realising this, the British government announced The Ten Point Plan for a Green Industrial Revolution, which set out a number of climate targets that the UK will follow to achieve net-zero by 2050[44]. This includes actions across the economy including increased renewable deployment, particularly offshore wind; ban on the sale of carbon-emitting passenger vehicles in 2030 and trucks by 2040; funding for zero-emission buses; and dedicated hydrogen targets such as the establishment of CCUS projects and 5GW low-carbon hydrogen capacity, amongst others.

[43] H2Live. Home. Accessed at: https://h2.live/en/ (2022).
[44] HM Government. The Ten Point Plan for a Green Industrial Revolution. (2020).

The UK was one of the last major European economies to publish its national hydrogen strategy[45], released in August 2021. This strategy detailed how the 5 GW low-carbon hydrogen production target will be achieved by 2030 – 1 GW by 2025 with a further 4 GW to be installed in the second half of the decade – but did not offer any increased ambitions from the government's Ten Point Plan. Unlike the EU, the UK's hydrogen strategy undertakes a 'twin-track' production approach which will help to position the UK as a world-leader in blue hydrogen production and CCUS technologies. However, since the Russian invasion of Ukraine, the UK have increased their ambitions and diversified their strategy in their newly published Energy Security strategy[46]. The UK will now target 10 GW of low-carbon hydrogen production by 2030, including 5 GW green hydrogen production, in an effort to produce larger amounts of low-carbon energy domestically.

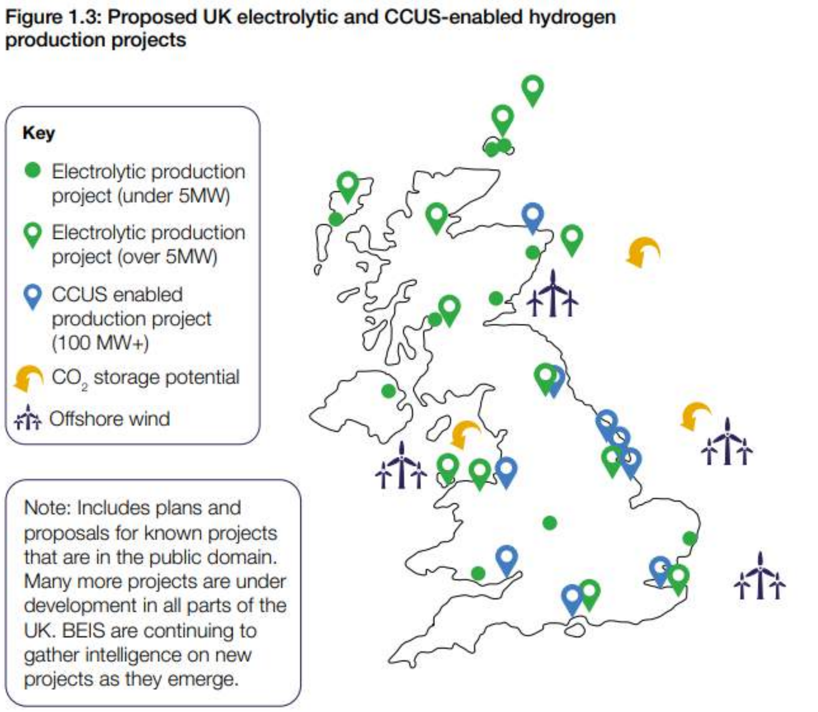

Figure 18*: UK Hydrogen production locations and resources as featured in the UK Hydrogen Strategy*

Alongside the launch of the National Hydrogen Strategy, following several government consultations, the UK launched the Net Zero Hydrogen fund – a £240m funding stream dedicated to minimising both the production cost, and commercial risks associated with low-carbon hydrogen production. This is the first of a suite of capital and operational support measures that the UK will be releasing in the coming years to incentivise further private investment in hydrogen activities. This includes a Hydrogen Business Model (HBM) which will provide dedicated operational support likely in the form of a Contracts for Difference (CfD) scheme.

Production - Current hydrogen production in the UK is concentrated around industry, specifically chemicals and refineries. Industrial clusters frequently produce hydrogen themselves via natural gas production pathways to ensure security of supply. Currently, Britain produces an estimated 10-27 TWh of hydrogen per year[45]. However, to achieve net-zero by 2050, it's predicted that Britain will need somewhere in the range of 250-460 TWh of low-carbon hydrogen – which will help to address between 20-35% of Britain's final energy consumption. This is likely to be met largely, at least in the short term, by blue hydrogen production as per governmental hydrogen goals. Although the UK, due to their increased energy security targets and domestic electrolyser manufacturers (ITM Power etc.), are now placing an additional focus on the role of green hydrogen within the country's energy system.

[45] HM Government. UK Hydrogen Strategy. (2021).
[46] HM Government. British Energy Security Strategy. (2022).

Applications - The UK is heavily favouring industrial deployments of low-carbon hydrogen. These are areas with significant experience in handling hydrogen that can provide a baseload demand to deliver security of demand whilst also offering the most cost-effective carbon abatement costs. Therefore, the largest UK low-carbon hydrogen projects, such as BP's blue hydrogen plant in Teesside, are all connected to industrial hubs. The largest currently announced green hydrogen project – Tees Green Hydrogen – will deploy an initial 30-50 MW of electrolysis capacity connected directly a local offshore wind farm. If successful, this project could be scaled to over 500 MW of capacity. Both are located proximally to the east coast industrial clusters of Teesside and Humberside.

The UK expects depot-based transport applications – such as return to base bus and truck fleets – to make up the bulk of transport hydrogen demand for the next decade. New subsidies and incentives have been launched, such as the Zero Emission Bus Regional Areas (ZEBRA) scheme, to incentivise the introduction of zero-emission mobility. The £120 million fund to deliver 4,000 new zero-emission vehicles and their required infrastructure starting in 2021, which will include FCEVs alongside BEVs.

The UK recognises that heavy-duty mobility applications are an effective user for hydrogen and are readily investigating the deployment of hydrogen HGVs. This position has been welcomed by the private sector who are readily forming partnerships to accelerate the deployment of hydrogen for heavy mobility. For example, Daimler and BP announced in October 2021[47] that the two had signed an MoU to assess the feasibility of jointly establishing a heavy-duty hydrogen refuelling network for up to 25 stations across the UK by 2030. The UK's strategy has been successful driving private investment due to their Renewable Transport Fuel Certificates (RTFCs). These RTFCs offer suppliers of hydrogen to road transport a considerable per kilogram subsidy which can tip the balance of business models from unviable to profitable. The UK is also investigating hydrogen for heavy mobility within maritime and aviation – both as a direct fuel and as part of synfuel production pathways.

To realise road-based hydrogen mobility the UK will need to expand their current refuelling infrastructure significantly. In 2015, the UK's first hydrogen mobility project was started but it has laid largely dormant for whilst governments have fumbled with Brexit instead. In its first iteration a plan for 65 HRSs was developed but to date just 14 refuelling stations are operational in the UK. A further 4 for cars and 4 for buses are planned but there are currently no plans for a government-backed UK-wide network.

Heat comprises almost 25% of all UK emissions and therefore represents a key decarbonisation opportunity for the use of hydrogen within the UK economy. The UK, as part of the HyDeploy project, has already successfully tested hydrogen-blending within natural gas infrastructure, with Energy Networks Association, the gas grid industry body, saying the entire UK grid will be ready to blend 20% hydrogen by 2023[48]. Plans have been established to trial the feasibility of a 100% hydrogen heating network within a neighbourhood by 2023, moving to a village-scale pilot in 2025 and a whole town by the end of the decade. The government are also considering requiring new NG boilers to be 'hydrogen ready' by 2026 to enable a future transition to a hydrogen heating system.

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[47] BP. BP and Daimler Truck AG to accelerate the deployment of hydrogen infrastructure, supporting the decarbonisation of UK freight transport. 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).

[48] S&P Global Commodity Insights. UK's gas grid ready for 20% hydrogen blend from 2023: network companies. Accessed at: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/011422-uks-gas-grid-ready-for-20-hydrogen-blend-from-2023-network-companies (2022).

Market Forecast

To adequately quantify the export opportunity available to the HEAVENN region, the size and makeup of hydrogen demand from neighbouring regions must first be assessed. Inconsistencies amongst their hydrogen production capabilities and expected scale-up of demand will present an opportunity to establish export chains and add value back to the northern Netherlands.

Netherlands – Initial research carried out by Energy Engineers as part of the TSO2020 project[49] – HEAVENN's precursor project – assessed how the demand of five regions across northern Netherlands and northwest Germany would scale over the next two decades (Drenthe, Friesland, Groningen, Lower Saxony, and North Rhine-Westphalia (NRW)). Whilst the European hydrogen sector has progressed significantly since its publication, the study showcases a number of key trends synonymous with the industry's recent development.

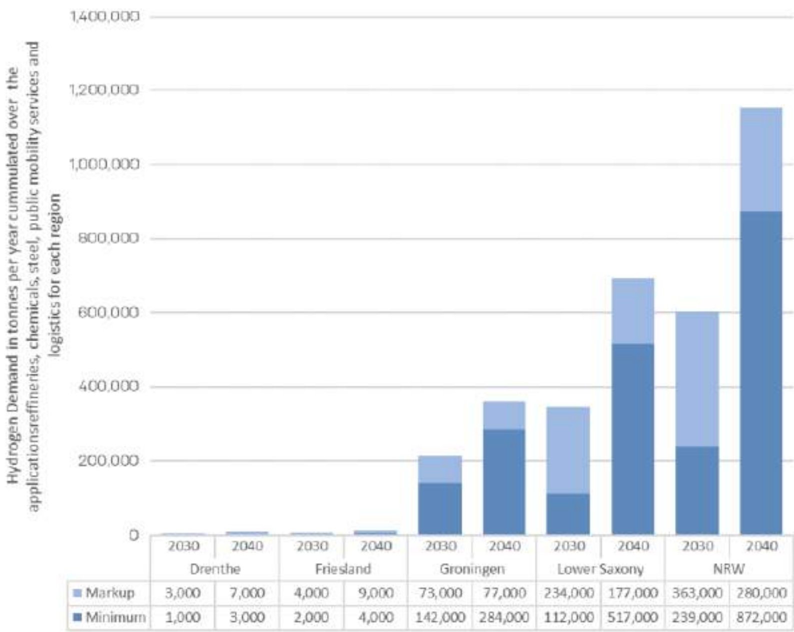

Figure 19*: Expected Hydrogen demand increases for proximal areas to the HEAVENN region* - Energy Engineers

This includes the regional specificity of hydrogen demand both in terms of overall volumes and end-users, and the dramatic expected increase of hydrogen demand between 2030 and 2040. The middle of the 2030s is predicted to be a critical juncture in the hydrogen sector's growth as technologies relating to both production and end-user applications become sufficiently mature to support each other, rather than exhibiting the current 'chicken and egg' scenario plaguing the sector. Of the three Dutch territories investigated, Groningen, due to its chemical cluster in Delfzijl, exhibits by far the largest hydrogen demand out to 2040 – over 25 times larger than that of Drenthe and Friesland.

As part of the HyNetherlands project and roadmap, ENGIE have carried out a hydrogen market study to quantify the hydrogen demand within the north Netherlands. The study, which was produced prior to the Russian invasion of Ukraine, assess three scenarios of differing hydrogen deployment:

- **Electrified World** - where direct electrification is seen as the premier choice of decarbonisation technology, with hydrogen used in some critical sectors such as maritime.
- **Blue Hydrogen** – decarbonisation via hydrogen is prioritised when deemed efficient, but only using blue hydrogen with no European Hydrogen Backbone.
- **Hydrogen rich** – Mix of blue and green hydrogen production used to efficiently decarbonise an increased proportion of the economy, with the presence of the European Hydrogen Backbone.

[49] Energy Engineers. Potential Market Uptake for Hydrogen in the Northern Netherlands and Adjacent German Regions. (2019).

Geopolitical pressure surrounding the use of Russian NG within Europe has led to a lack of momentum surrounding the implementation of blue hydrogen technologies within Europe. Furthermore, with greater desire to develop green hydrogen production domestically, following the announcement of the REPowerEU initiative, it was concluded that the Hydrogen rich scenario is the most applicable to the current day European energy landscape.

Within this scenario, hydrogen demand is expected to grow to roughly 320 TWh by 2050. Other earlier studies/analyses have this figure at ~150TWh. The acceleration of renewables via RePowerEU therefore appears to increase the need for hydrogen to play a prominent role. Blue hydrogen production will scale to 2030, at which point green hydrogen will become cost competitive and dominate further market growth until it accounts for 85% of domestic production within the Netherlands with a 48 GW of total installed electrolysis capacity. Domestic production will only satisfy roughly 45% of national demand, therefore requiring import value chains to help overcome the remainder in the form of hydrogen derived fuels. However, due to the Netherland's unique strategic infrastructure position within Europe, the country will actually be a net exporter of hydrogen to neighbouring countries through the European Hydrogen Backbone by 2030.

The Hy3 project, which seeks to deploy large-scale offshore hydrogen production coupled to offshore wind to decarbonise Dutch and German industry, also analysed the potential hydrogen demand of both the Netherlands and the NRW region. It can be seen from figure XXX[50] that Dutch hydrogen demand is expected to be overwhelmingly dominated by refineries and power-to-liquid processes in the long-term, centralised around South Holland and Zeeland. However, a decentralised supply of hydrogen will also be required across the whole of the Netherlands to satisfy mobility, particularly along key transport corridors such as the TEN-T corridor networks.

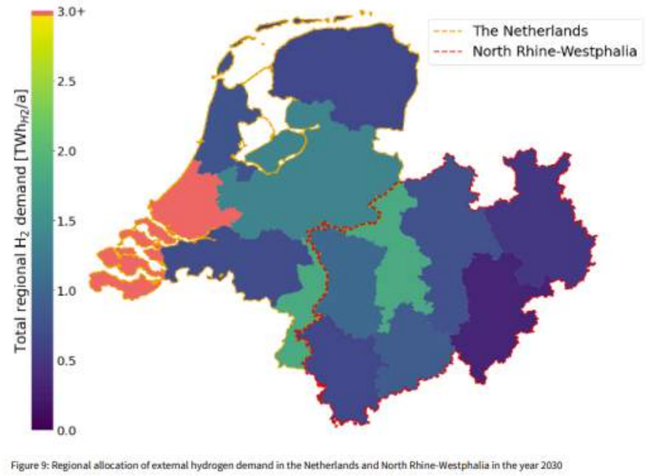

Figure 20*: 2030 expected demand by region in the Netherlands* - Hy3 Feasibility study

As a leading Dutch region in the production of low-carbon hydrogen, these studies showcase the opportunity available to the HEAVENN region to export hydrogen nationally. This export position will be enabled in the short-term via the introduction of Gasunie's hydrogen ring and pipeline system which will allow for the movement of large volumes of hydrogen, without the need to implement cross-border hydrogen legislation. As the Dutch hydrogen sector continues to grow out to 2050 (see figure XXX), the HEAVENN region, through its ports such as Eemshaven, will behave as a landing point for internationally produced hydrogen and will thus help to further satisfy hydrogen demand via redistribution of foreign product, as well as distribution of locally produced green hydrogen.

[50] TNO, Julich Forschungszentrum, dena. Feasibility study Hy3. (2022).

Germany – At 55 TWh per annum, Germany is the largest hydrogen consumer within Europe. The country's national hydrogen strategy will ensure Germany maintains this leading position by both increasing demand within existing industrial sectors, such as chemicals, and introducing demand into new areas of the economy, like mobility. Reports vary on the size of Germany's potential hydrogen demand in 2050 - 300-900 TWh for all hydrogen and hydrogen derived fuel requirements - but all recognise the importance of imported hydrogen in satisfying this demand. Imported hydrogen supply is expected to become the leading source of hydrogen in Germany by 2040, growing to supply 75% of the country's demand in 2050 – equating to between 225-675 TWh of hydrogen-related products. Whilst for specific German regions, such as NRW, where large amounts of the country's industry is based, import dependency is expected to reach around 90%.

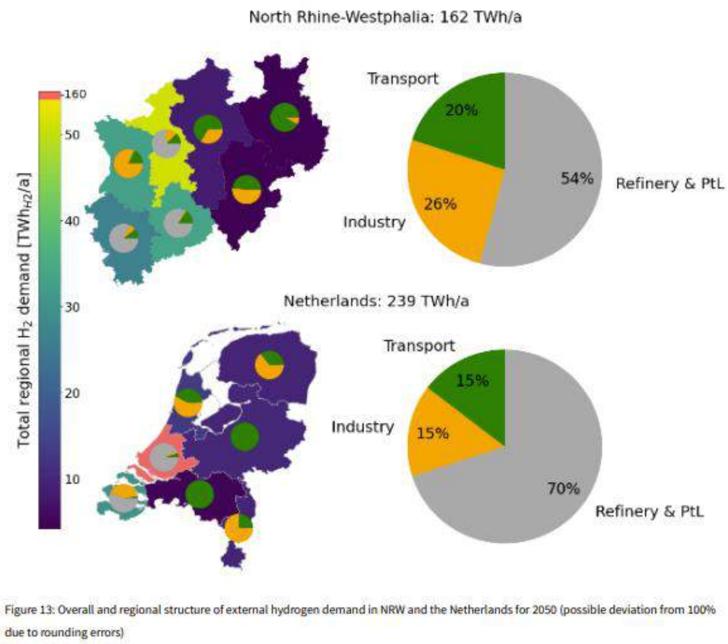

Figure 21*: 2050 expected hydrogen demand by region and sector in NRW and Netherlands* - Hy3 Feasibility study

The Hydrogen Strategy for North Germany, released in 2019, recognised that Germany's renewable energy potential would not be sufficient to satisfy the regions' (Bremen, Hamburg, Mecklenburg-Western Pomerania, Lower Saxony, and Schleswig-Holstein) hydrogen demand. To achieve net-zero, imports of hydrogen will be required to Northern Germany, particularly to satisfy the needs of local industrial demand. It is expected that existing import terminals, such as established seaports, will take precedence due to their experience handling large amounts of fuel. Greater amounts of international co-operation is required, however, to achieve the necessary scale to not only replace current fossil-based hydrogen feedstocks, but also allow for further sector growth.

To gain access to greater amounts of hydrogen, national pipeline infrastructure is being planned as part of both public and private infrastructure projects. RWE and gas transmission operator OGE, as part of the H2ercules plan, will build 1,500km of pipelines to transport green hydrogen across Germany[51], linking storage, import facilities, and industrial customers together through one system. Whilst a recent draft strategy paper from the German economy ministry details how Germany will develop a 1,800km hydrogen pipeline network by 2027, with state participation, including plans to import hydrogen as part of their strategy to reduce reliance on Russian gas[52]. It is not yet clear whether these two plans are mutually exclusive.

Germany is readily aiding the development of international hydrogen value chains, both with the purpose of exporting domestically produced technologies, and importing hydrogen from these locations in the long-term as part of H2Global. Today, this has resulted in little increased activity

[51] RECHARGENews. RWE plans 1,500km hydrogen pipeline grid through Germany. Accessed at: https://www.rechargenews.com/energy-transition/from-the-north-to-steelworks-rwe-plans-1-500km-hydrogen-pipeline-grid-through-germany/2-1-1191078 (2022).

[52] Reuters. Germany plans 1,800km hydrogen pipeline network: draft government paper. Accessed at: https://www.reuters.com/business/sustainable-business/germany-plans-1800-km-hydrogen-pipeline-network-draft-government-paper-2022-12-02/ (2022).

within the Netherlands. However, the inclusion of companies such as Gasunie and Air Products, who are integral players within the Dutch hydrogen sector, and the recent announcement that the Dutch government will participate financially within the initiative - to intensify co-operative activities relating to hydrogen purchasing regulations and cross-border infrastructure[53] – will likely result in a more aligned position that the Netherlands will be able to engage with.

Due to their proximity to the HEAVENN project region, German regions like NRW, who exhibit high hydrogen demand, with relatively low local production capabilities, are ideal locations to initialise cross-border trade of low-carbon hydrogen. Projects, such as Hy3 and Hansa Hydrogen Hubs, are already investigating the opportunity to establish cross-border hydrogen projects by exploiting the synergistic properties of the two regions, such as local ambitions for 100% hydrogen pipelines. These pipelines could be linked together to provide an exemplar for cross-border hydrogen trade by 2030 for the rest of Europe to learn from as the wider EHB initiative is rolled-out. Furthermore, with the decades of large-scale operational hydrogen knowhow across the hydrogen value chain, Netherlands and Germany are the best locations within Europe to initialise cross-border hydrogen trade.

UK – Analysis carried out by the UK's department for Business, Enterprise, and Industrial Strategy, for the development of the government's hydrogen strategy[54], suggests that domestic hydrogen demand could reach 250-460 TWh by 2050 – equal to 20-35% of the country's final energy consumption. Today, the UK produces just 27 TWh of hydrogen primarily from grey sources, but this is likely to grow significantly over the coming decade. The UK's sole low-carbon hydrogen production target – 10GW by 2030 – will add a further 88TWh of production capacity, where 1GW of capacity equates to 8.76 TWh.

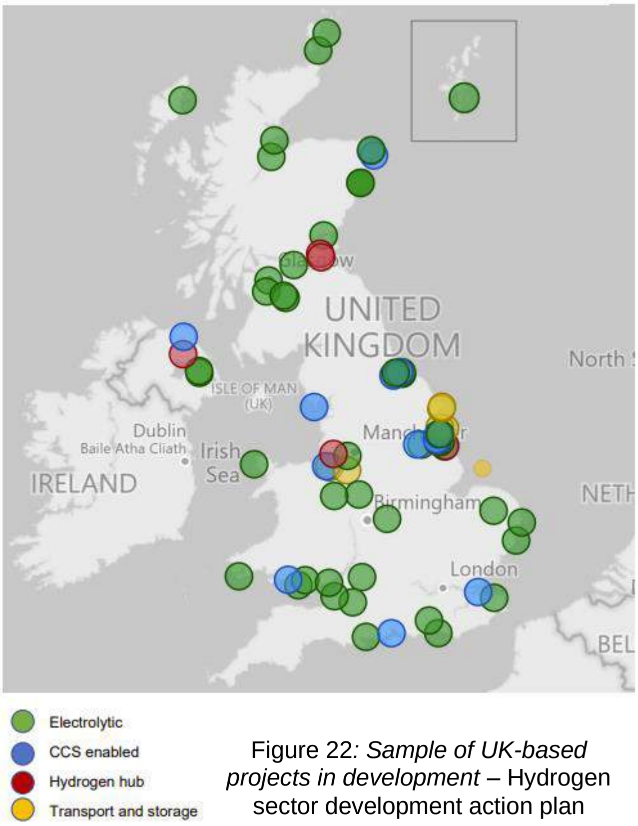

Figure 22: *Sample of UK-based projects in development* – Hydrogen sector development action plan

Whilst the UK is prioritising the development of the domestic market, the country expects to be an 'active participant within international markets' too. The majority of this international participation will focus on the export of UK-produced hydrogen to lucrative foreign markets. However, there will also be a need for imported hydrogen to add redundancy by broadening supply chains, and gain access to greater amounts of hydrogen to scale-up the UK's hydrogen sector – exemplified by the difference of the UK's current targets and projected 2050 hydrogen demand.

Developments regarding the import of hydrogen to the UK will be focused, in the short-term, around the country's seaports. These locations are already key import locations for oil and gas and are expected to become key landing sites for large-scale, offshore renewables in the future, particularly

[53] German-Dutch climate cabinet. Together on the path towards neutrality. Accessed at: https://www.bundesregierung.de/breg-en/news/german-dutch-climate-cabinet-2131744#:~:text=The%20Dutch%20government%20is%20planning,of%20hydrogen%20at%20regulated%20conditions. (2022).

[54] HM Government. UK Hydrogen Strategy. (2021).

those based on the east coast with access to the North Sea. Seaports will provide the UK with access to low-cost hydrogen from key non-European renewable hotspots, such as the Saudi Arabia and Oceania, as is being explored by the country's private sector. The UK's public sector, however, is yet to announce formal partnerships with any foreign governments exploring import/export chains but has funded reports assessing theoretical import value chains. These value chains include both green and blue hydrogen in various forms – gaseous pipeline deliveries, shipped liquid hydrogen, and shipped energy vectors (Ammonia, and LOHCs). It was found that gaseous pipeline deliveries of green hydrogen from European destinations would lead to the most advantageous emissions intensity of the assessed pathways, whilst imports via ship were also competitive with domestic production as long as the production pathways are green, large-scale, and the ships used are suitably efficient.

Further commitment to developing a national large-scale domestic hydrogen sector, can be seen by the announcement of the UK's NG grid operator, National Grid, to deploy a 100% hydrogen pipeline network that links the country's largest hydrogen users – industrial clusters. The project, titled 'ProjectUnion[55]', will repurpose 25% of the country's NG grid, to deliver a 2,000km hydrogen pipeline network across the UK by 2030. This will be critical in realising emissions savings across UK industry, and potentially heating too, acting as a key project proving the feasibility of large-scale distribution and use of hydrogen before the UK switches the rest of the NG infrastructure in the future. The UK is a leader in the use of hydrogen in gas grids, having already announced that the country's NG grid will be ready to accept a blend of 20% hydrogen by 2023. ProjectUnion will also assess the opportunity to convert existing interconnectors to hydrogen, which could include the Bacton Gas Terminal's connection to Balgzand in Netherlands.

The UK's long-term import position is also anticipated within DNV's UK Energy outlook 2022[56]. Whilst overall energy imports will reduce, because of an increased focus on energy independence and reduced total energy consumption, they will still play an important role in satisfying the UK's final energy demand in 2050. Hydrogen will be imported in the form of ammonia to both directly, and indirectly via transformation, help address the emissions of the transport industry – particularly maritime, aviation, and road transport, although domestic exports of hydrogen will far outsize this. However, in line with recent analysis, the outlook expects hydrogen to make up a minimal amount of the UK's space heating demand, unlike National Grid's predictions. The House of Common's

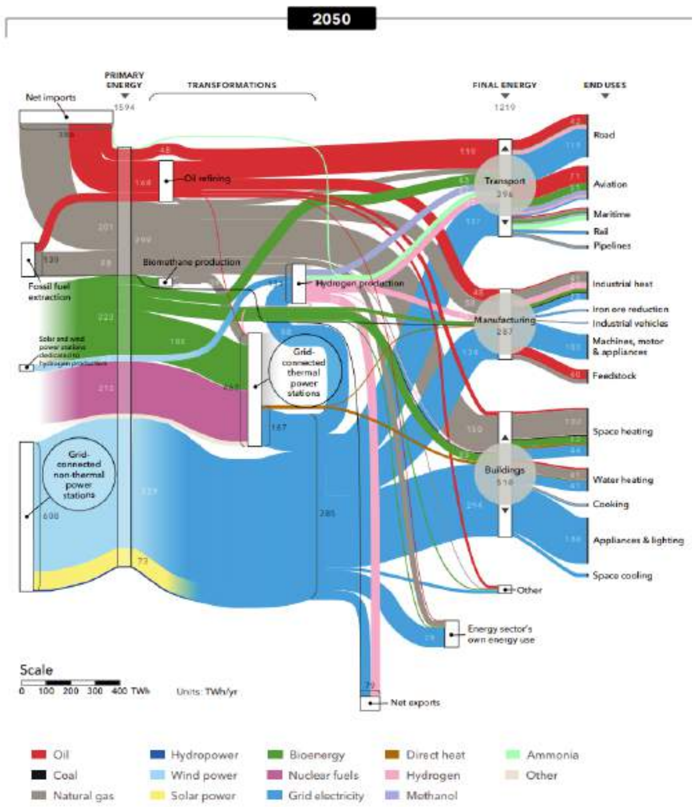

Figure 23*: UK 2050 Energy Landscape - DNV*

[55] nationalgrid. ProjectUnion Launch Report. (2022).
[56] DNV. UK Energy Transition Outlook 2022. (2022).

Science and Technology committee[57], and DNV, have stated that a lack of decision-making surrounding support measures, business models, and a clear and defined roadmap could stall the implementation of hydrogen for heat technologies. Whilst a review carried out by a member of the Regulatory Assistance Project[58], has called into question the viability of these technologies. It has stated, following comparison of 32 studies, that hydrogen is "less economic, less efficient, more resource intensive and associated with larger environmental impacts" in comparison to other low-carbon heating alternatives, such as heat pumps, potentially doubling consumer's bills. This, therefore, raises concerns about the long-term bankability of the UK's hydrogen sector both in terms of domestic growth potential, and as an export offtaker.

Overall, the UK does not represent a short-term export opportunity for the HEAVENN region, due to a lack of interconnectivity between the two area's hydrogen activities. However, this could change after 2035 when the two grid infrastructures become more joined as a result of ProjectUnion and the EHB initiative. In addition, an initiative by north-east Scotland, which has excess renewables, to look at using existing North Sea extraction oil and gas pipelines to connect across to the Netherlands would also enable serve as a further integration step.

The UK's recently released hydrogen strategy market update[59], states that due to the development of the global hydrogen trade, the UK market could feature "a greater role for imports" to both help build supply chain resilience, and further energy security. Piped green hydrogen from mainland Europe, including the HEAVENN region, could thus be regarded as short- to medium- term premium product which can enable domestic sector growth at minimal climate cost. However, the UK still expects to be a net hydrogen exporter long-term and will establish the necessary certification systems by 2025 to enable this position, with established energy trading locations the likely recipient of this distributed product.

The Opportunity for Export - 2030

The HEAVENN region is uniquely positioned to be one of the first locations to realise interregional and international trade of low-carbon hydrogen. Its early mover position has provided the region with the necessary experience across production, distribution, applications, policy, and safety to expand beyond its initial domestic position to investigate linking with lucrative transnational and foreign markets by 2030.

In this initial timeframe, exports to the wider Netherlands will dominate the HEAVENN region's export potential. The current lack of clarity surrounding both the physical viability and policy environment of international hydrogen trade, coupled with a desire from the Dutch government to greatly reduce emissions of domestic activities, will result in greater hydrogen volumes traded on a national basis. National trade within this timeframe has considerable advantages over international.

Firstly, Gasunie's hydrogen ring network will provide dedicated national distribution infrastructure that connects key national industrial clusters together by 2025. This infrastructure will join the HEAVENN region to the largest consumers of hydrogen in the Netherlands which will become not just viable off-takers, but a critical growth opportunity to scale regional hydrogen production.

Secondly, strategies, policy, and funding directed to hydrogen activities within the Netherlands have been focused on the development of a domestic hydrogen sector. This includes both the launch of a national certification system for the supply of renewable energy into the transport sector, and

[57] House of Commons Science and Technology Committee. The role of hydrogen in achieving Net Zero. (2022).
[58] Rosenow. Is heating homes with hydrogen all but a pipe dream? An evidence review. (2022).
[59] Department for Business, Energy, & Industrial Strategy. Hydrogen Strategy update to the market: December 2022. (2022).

hydrogen guarantee of origin scheme as part of the HyXchange initiative[60]. These systems are only valid within Netherlands and understanding, and implementing, the necessary alterations to make them internationally compatible will be a laborious and time-consuming process. Instead, Dutch producers will favour selling products domestically due to bankability of business models surrounding these certification systems.

The only exception to this rule is Germany. Germany, and in particular its western industrial clusters which are located next to the HEAVENN region, will require vast amounts of hydrogen which it cannot supply itself. Therefore, with recent collaboration between the Dutch and German government as part of the H2Global scheme and a desire to co-operate on EHB activities, hydrogen exported to Germany from the HEAVENN region could act as a critical first step to establishing cross-border activities. As part of the EU's recent large-scale cross-border hydrogen valley funding call, a number of projects, such as Hansa Hydrogen Hubs (H3)[61], have sought to exploit this link between the two countries to initialise hydrogen trade. As part of this call, the EU, recognising the importance of international movement of hydrogen, necessitated projects to trade at least 20% of their minimum 5,000 tonnes/annum low-carbon hydrogen production across borders. Although the focus of the HEAVENN project is to enable domestic decarbonisation via the use of low-carbon hydrogen, the project's extension, together with the acceleration of the EU hydrogen sector, have placed an added emphasis on cross-border hydrogen co-operation. Therefore, if the necessary harmonisation of standards, practices, and policy, occurs between the two states, it is possible that up to 10% of HEAVENN produced hydrogen could be distributed into NRW and Lower Saxony to help satisfy their local industrial demand – which could reach in excess of 300,000 and 600,000 tonnes/annum respectively[62]. Meanwhile, more geographically separated countries, such as the UK will have limited hydrogen trade with the HEAVENN region by 2030. The mismatch in infrastructure deployment timelines, and lack of current international co-operation with the Netherlands will be too much to overcome in this period but is likely change more rapidly once an initial international trading template has been established. So, a timeline between 2035 and 2040 might be expected.

By contrast, in 2030, it is expected that approximately 20% of hydrogen produced in the HEAVENN region could be distributed nationally, with the majority moved via national pipeline infrastructure to the east of the country, particularly Rotterdam and Zeeland. These two regions, which will both feature hydrogen demand in excess of 3 TWh_{H2}/annum by 2030[63], are the country's leading hydrogen users due to the prevalence of industrial and refinery applications. Rotterdam's position as a leading energy processing location for the whole of Europe, will also see the region import hydrogen for distribution to other locations across the continent.

Nonetheless, in line with the HEAVENN's project objectives, locally produced hydrogen will still be prioritised into applications across the project's six clusters based within the northern Netherlands – Eemshaven, Delfzijl, Zuidwending, Emmen, Hoogeveen, and Groningen – over international markets during this period. At least 70% of the region's production capacity is expected to be retained for local use, with the primary driver being Groningen's chemical industry – final demand from which is expected to grow to in excess of 200,000 tonnes/annum over the time period[64]. Demand from mobility applications in the Netherlands is also expected to grow across this timeframe reaching 5TWhH2/annum . Hydrogen refuelling stations, however, are likely to be serviced by small-scale regional production hubs connected to local hydrogen valley style development. Therefore,

[60] HyXchange. Accessed at: Hyxchange.nl (2022).
[61] Cnubben. From HEAVENN to Hydrogen Valleys, Transition to Hydrogen economy. (2022).
[62] Energy Engineers. Potential market uptake for hydrogen in northern Netherlands and adjacent German regions. (2019).
[63] TNO. Feasibility Study Hy3. (2022).
[64] Energy Engineers. Potential market uptake for hydrogen in northern Netherlands and adjacent German regions. (2019).

transport demand that will be serviced by hydrogen produced within the HEAVENN region will be minimal when compared to the country's industrial demand.

Like Rotterdam, the HEAVENN region already behaves as an energy distributer through its ports and coastal energy production cluster. Following the Russian invasion of Ukraine and the announcement of REPowerEU, it took the EemsEnergyTerminal project just six months to deploy a functional floating LNG terminal at the port of Eemshaven. The terminal, which accepted its first shipment in September 2022, will be critical to helping reduce reliance on Russian gas within the Netherlands and Europe through its 8 Bcm/year capacity[65]. Over the coming decade, Eemshaven will have to grow its energy handling capacity to maximise renewable energy capture from sources in the North Sea. The most likely onshoring route for this energy is via direct electrical cabling. Although, production of green hydrogen and distribution via pipelines and ships is also being explored as a cost-effective way of distributing energy from offshore energy sources. Furthermore, with imports of green hydrogen from renewable hotspots expected to also be realised by 2030, the economic and energetic potential for the region with relation to hydrogen processing is considerable. This opportunity is time sensitive, however. If Rotterdam and Hamburg, two critical European ports who have already announced intentions to build hydrogen import capabilities, seek this position more rapidly, then Eemshaven could be left with a limited market to exploit. Instead, if the port focuses imminent resources to build hydrogen import handling capabilities, by expanding/diversifying current activities on projects such as Eemshydrogen, then, using its existing well-developed energy distribution infrastructure, it could become a key energy processing location for the Netherlands and Europe.

The Opportunity – 2050

Whilst the expected size of the global hydrogen sector in 2050 varies, the technologies, supply chains, and trading routes that make up the sector will have reached full maturity. Green hydrogen will be available at significantly larger scales and lower costs internationally due to extensive global distribution infrastructure. The HEAVENN region, as one of the world's leading green hydrogen regions, will continue to utilise its expertise to produce, distribute, use, and export more hydrogen in 2050.

Local decarbonisation will still be prioritised come mid-century, particularly for the replacement of chemical industry feedstocks and heavy-duty road and maritime fuels - both pure hydrogen and other hydrogen-derived compounds. These areas will utilise clean energy solutions to both mitigate existing emissions and enable further sustainable growth, therefore resulting in a greater demand for hydrogen from an increased number of customers in 2050 compared to 2030. However, as familiarity with hydrogen grows, hydrogen will be used as a commodity on a national scale, similar to natural gas, helping dynamically satisfy demand hotspots, such as Rotterdam and Zeeland, and a decentralised transport network via interconnecting distribution infrastructure. Thus, whilst the overall volume of hydrogen produced and used domestically within the HEAVENN region is expected to increase, the overall proportion will decrease to roughly 30% due to increased opportunities to export to other Dutch regions – also roughly 30% - and internationally.

The HEAVENN region's long-term potential as a distributer of energy from international value chains will be highly dependent upon the energy strategies and policy framework set by the region itself, Dutch government, and European Commission over the next 10 years. The region will almost certainly behave as an onshoring point for North Sea energy projects, featuring both direct electric cabling connections and hydrogen pipelines, but to gain access to internationally traded hydrogen

[65] REUTERS. First LNG shipment arrives at new Dutch floating terminal. Accessed at: https://www.reuters.com/business/energy/first-lng-shipment-arrives-new-dutch-floating-terminal-2022-09-08/ (2022).

will require greater political impetus. If the HEAVENN region does become a hydrogen import terminal, then imported product is likely to outsize domestic production capabilities by 2050. The scale of international hydrogen value chains by mid-century will deliver incredibly large amounts of low-cost hydrogen to Eemshaven and the surrounding area for distribution across Europe. This hydrogen will somewhat help to satisfy domestic and national hydrogen demand by ensuring security of supply but will overwhelmingly be placed into the EHB to be distributed and traded on a European-wide hour-by-hour basis.

Regardless of the future of Eemshaven's energy capabilities, an increase in the maturity of hydrogen pipeline infrastructure and development of global cross-border trade legislation, including internationally recognised GoO systems, will result in greater international trade of hydrogen when compared to 2030. For the HEAVENN region, this will manifest in the form of greater trade with proximal nations, such as Germany. Germany will continue to be the leading non-domestic off-taker of hydrogen produced within the HEAVENN region, particularly the regions of Lower Saxony and NRW. The need for low-carbon hydrogen to replace the industrial feedstocks within these two regions is one of the leading drivers of Germany's hydrogen policy. Therefore, by 2030, the HEAVENN region will export roughly 30% of its domestic hydrogen production capacity to Germany. It is expected that imported hydrogen would be traded with Germany in even higher proportions if this position were to be realised.

Extended pipeline connections will enable trade of hydrogen with alternative end-user destinations such as Belgium, France, and the UK. However, with national decarbonisation taking precedent over other pathways, these countries are only likely to receive c. 10% of the total hydrogen handled within the HEAVENN region. This hydrogen will not be traded directly with customers in these territories but instead through a wholesaler, similar to the oil and gas markets today. For these countries, this volume of hydrogen is unlikely to behave as a critical source of supply, but will make up one of a matrix of supply options to gain greater supply redundancy. For example, the UK, which will likely end as a net-exporter by 2050, might import just 2% of the hydrogen produced within the HEAVENN region. Whilst Belgium, who also expect to import for domestic use in 2050 as well as distributing renewable molecules internationally, could be an off taker for >5% of the region's production capacity. These percentages will vary greatly year-on-year but will give the region a greater security of demand through numerous offtakers in different geographical and political landscapes.

Conclusion

The cost, market, and policy analysis carried out in the previous sections of this report have been used to produce a set of informed supply pathway scenarios for the HEAVENN region. These scenarios showcase how different production, transmission, and end-use applications affect the cost of hydrogen available within the HEAVENN region and the costs associated with transmitting this hydrogen, via various mechanisms, to serve markets in neighbouring regions. These scenarios are:

Production Scenarios

4. **Green Local** – Green hydrogen produced at the port of Eemshaven via dedicated renewables.
5. **Blue Historic Local –** blue hydrogen produced at the port of Eemshaven using historic natural gas prices (pre-energy crisis).
6. **Blue Modern Local** – blue hydrogen produced at the port of Eemshaven, using modern-day natural gas prices.
7. **Green International** – Green hydrogen that is converted to ammonia and shipped from Saudi Arabia to Eemshaven. Ammonia is reconverted to hydrogen at Eemshaven.

Distribution Scenarios

8. **Regional Compression Hub (RCH)**– Hydrogen that is piped an average of 300km to a regional compression hub before it used to fill a gaseous tube trailer. This tube trailer then travels an average of 25km to make a delivery to its end-users.
9. **Direct Industrial Connection (DIC)** – Hydrogen that is directly piped to an industrial end user via a 300km pipeline.
10. **Liquid Hydrogen Distribution (LHD)** – Hydrogen that is liquefied at the port of Eemshaven and distributed by the liquid tanker to end-users and average distance of 300km away.

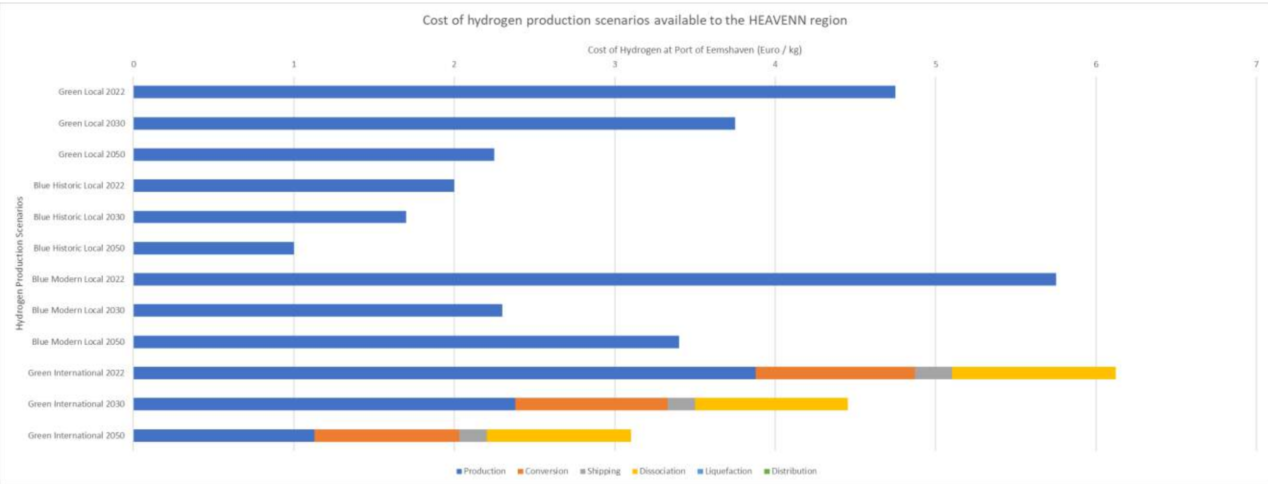

Figure 24*: Hydrogen cost analysis overview*

Of all production scenarios, the local blue hydrogen scenario using historic gas prices results in the lowest hydrogen production costs across all time periods. However, should natural gas prices continue near their recent highs, blue hydrogen production will be considerably more expensive – >100% increase across all time periods. Blue hydrogen production is expected to be the cheapest form of hydrogen production in 2030, using either modern or historic prices. In 2050, however, if the commodity's cost settle somewhere between these two modern and historic prices – €2.7/kg - it will struggle to compete with green hydrogen which features a lower cost – €2.31 - and lower carbon intensity making it more attractive to potential customers. It is worth noting that this analysis has not factored carbon tax increases within blue hydrogen production figures which will further increase production costs depending on leakage and capture rates. Currently, the price of emissions allowances traded on the EU's Emissions Trading System (ETS) is around €80/tonne$_{CO2}$. Emissions traded on the ETS are predicted to increase, eclipsing recent highs of €95/t achieved in August 2022, to €120/t by 2030 in order to achieve net-zero in expected timeframes. According to research carried out by the National Institute of Economic and Social research, increasing carbon taxes to $100/t, roughly equivalent to €93/t, much lower than the EU's expected required increase, would raise the price of gas and oil by 60-70% relative to renewables[66]. Therefore, increases beyond this amount by 2030 could bring blue hydrogen's production costs closer to green in a much shorter timeframe.

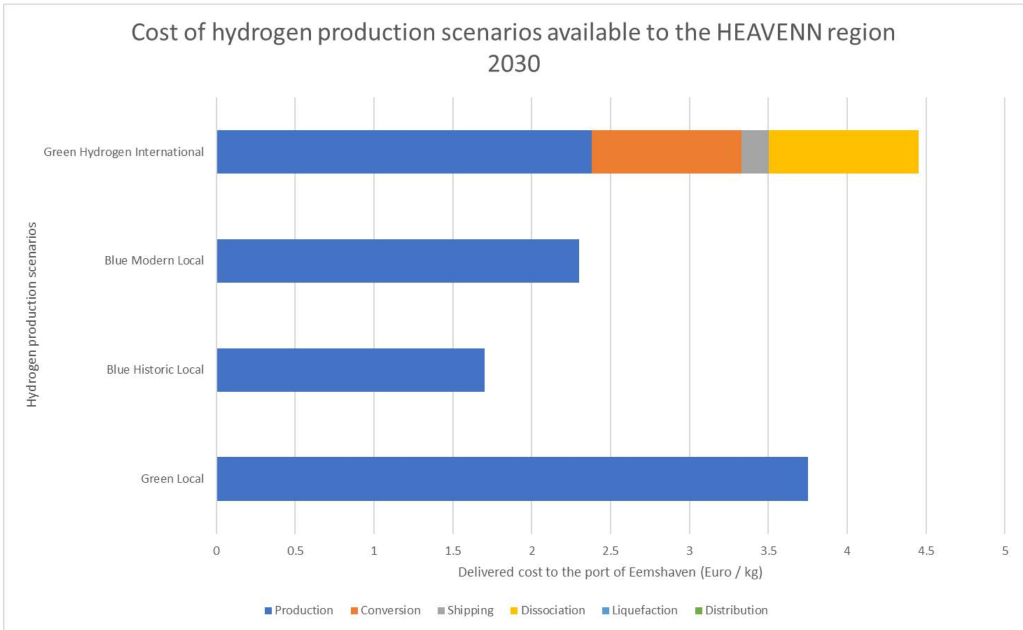

Figure 25*: 2030 Cost analysis*

The cheapest form of green hydrogen available in the HEAVENN region in 2030 will be via local production pathways. The cost of additional steps required by international production pathways – conversion, shipping, and dissociation – will make it difficult for such pathways to achieve parity with local hydrogen production. However, whilst international hydrogen is expected to be 14% more expensive in 2030, the overwhelming demand for hydrogen in northwest Europe will require the import of hydrogen at this price point, with governments offering financial support to mitigate the difference. The gap between local and international hydrogen will grow to 34% in 2050 as economies of scale in production technologies outweigh decreases in cost of already mature transformation and distribution processes such as ammonia production and shipping. By 2050 it is likely that all locally available hydrogen production pathways will have been exploited and market pricing will be based on variable import cost – much as we see with natural gas today – ensuring that import facilities will continue to be required and will expand.

66 National Institute of Economic and Social Research. The Macroeconomic Effects of Carbon Pricing. Accessed at: https://www.niesr.ac.uk/blog/macroeconomic-effects-carbon-pricing#:~:text=A%20%24100%20carbon%20price%20would,by%2060%2D70%20per%20cent.(2022)

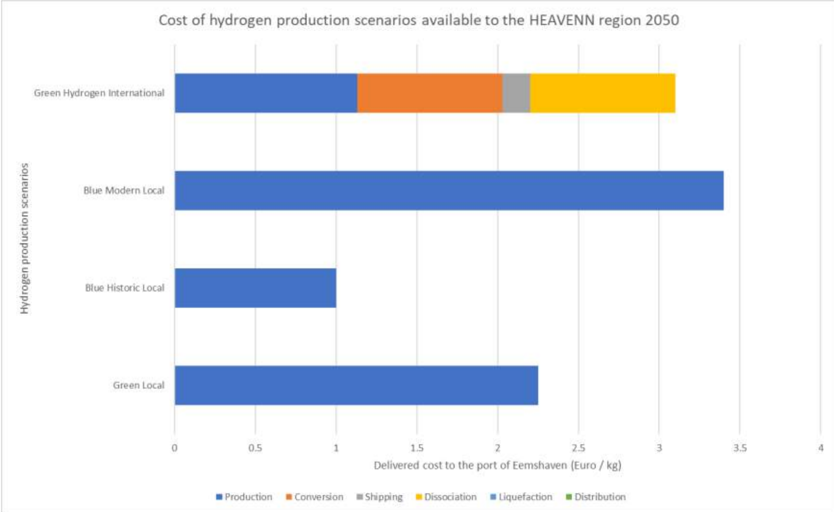

Figure 26*: 2050 Cost analysis*

In order to gain access to international hydrogen value chains the HEAVENN region must move quickly. The Port of Eemshaven must join other early moving ports, such as Rotterdam and Hamburg, in solidifying its position as a hydrogen import terminal to maximise its international energy trading position. As an expected major hydrogen importer, the Netherlands will need to ensure both scale and security of supply via multiple import terminals, similar to the EU's fast-paced development of LNG terminals to diversify supplies away from Russian natural gas.

Eemshaven must engage with stakeholders across the value chain to join the port's potential hydrogen throughput to bankable offtakers. These could include offtakers based proximally, such as methanol producers at the Delfzijl chemical cluster, potentially as way to enable scale-up of the HyNetherlands project concept, or across Europe via the port's energy interconnectors and envisaged linkage to the European Hydrogen Backbone. As part of these activities, analysis of the viability of key infrastructure facilities on/or close to Eemshaven including an ammonia import terminal and cracker, a liquid hydrogen plant and tanker filling terminal and hydrogen gas distribution infrastructure (pipelines and tube trailer filling systems) should be undertaken.

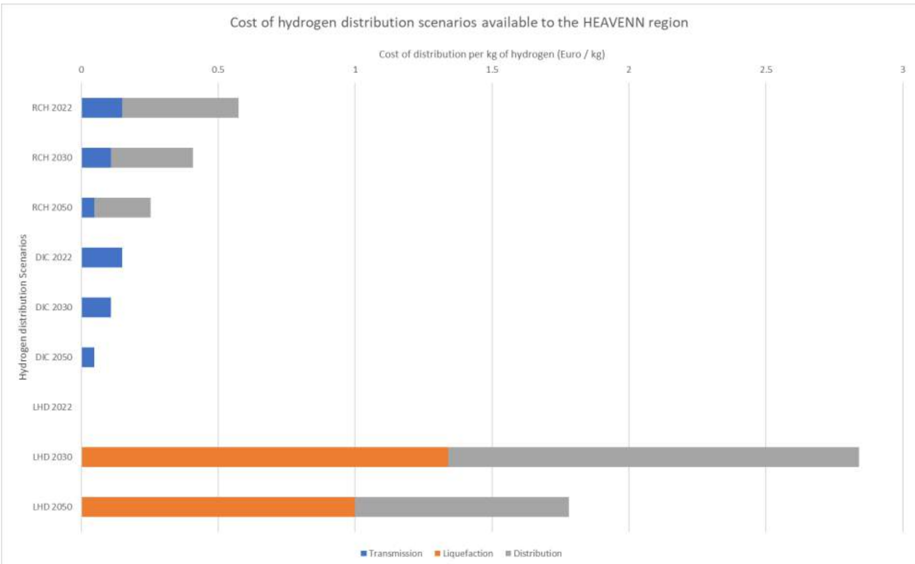

Figure 27*: Hydrogen distribution analysis overview*

Distribution analysis included in Figure 27 has assumed an average customer delivery distance of 300km – similar to the distance between Eemshaven and industry based in the west of the Netherlands or Germany (e.g. Cologne). Unsurprisingly distribution of hydrogen straight to customers via a direct pipeline leads to the lowest distribution costs (scenario 6). Pipelines, due to their ability to transfer incredibly large throughputs of hydrogen with relatively low operational costs make them ideal for large-scale customers. In scenario 5 national and European pipeline systems, such as the European Hydrogen Backbone, enable small-to-medium scale applications to gain access to hydrogen without the need for large amounts of CAPEX on pipelines via connections to regional compression hubs and trailer filling infrastructure. The addition of tube trailer deliveries adds significant distribution costs, of €0.42/kg in 2030 and €0.24/kg in 2050, but its lower capital barrier and added adaptability will necessitate its use and promote a geographic broadening of hydrogen end-users. These costs would be anticipated to be at least as good as those available from other key coastal locations i.e. Rotterdam or Hamburg.

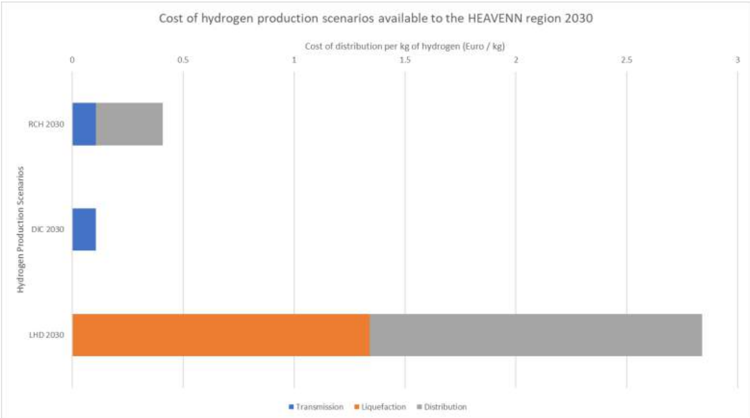

Figure 28*: 2030 distribution analysis*

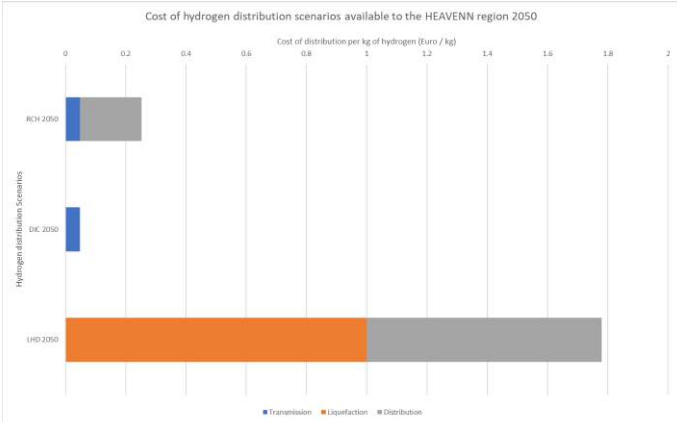

Figure 29*: 2050 distribution analysis*

Liquid hydrogen is inherently more expensive due to the addition of the liquefaction process. However, it is worth noting that liquid hydrogen will not be competing with gaseous hydrogen. Liquid hydrogen will have its own specialist applications – such as AFIR refuelling stations or aviation – and thus its premium will not inhibit its competitiveness. Liquefaction is currently carried out on a small-scale across a number of plants in Europe for bespoke applications. Therefore, as these plants are not located in the region scenario 7 has not been considered for 2022. As demand for liquefied hydrogen increases, liquefiers will increase in size and be based closer to their end users or co-located in large industrial locations such as ports where hydrogen is plentiful. Innovation in this area, particularly storage technologies and processes, is also expected as can be seen through the Clean Hydrogen Partnership's choice to fund LHY refuelling stations. Thus, the cost of liquefaction and distribution are expected decrease significantly as can be seen from Figure 28 and Figure 29 – where total distribution costs decrease 60% from €2.84/kg in 2030 to €1.78 in 2050.

Therefore, given this analysis, the opportunity for the HEAVENN region to provide hydrogen to its near neighbours both within the Netherlands and across its borders is confirmed. The amount of hydrogen available, both from local production and the potential to supplement these with further imports, exceeds local demand profiles. The assessed cost of the hydrogen available and the cost to transfer it to neighbouring markets are expected to be competitive with other supplying pathways available to these areas. Key to developing a position in a wider hydrogen supply market will be the region's intent to develop hydrogen facilitating infrastructure across the Eemshaven/Delfzijl corridor.

HEAVENN

Clean Hydrogen Partnership

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