SUSTAINABLE HYDROGEN

INDUSTRY TRANSITION PLATFORM

A report for

The Climate Group

Element Energy

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This report has been prepared by Element Energy.

Element Energy is a strategic energy consultancy, specialising in the intelligent analysis of low carbon energy. The team of over 70 specialists provides consultancy services across a wide range of sectors, including the built environment, carbon capture and storage, industrial decarbonisation, smart electricity and gas networks, energy storage, renewable energy systems and low carbon transport. Element Energy provides insights on both technical and strategic issues, believing that the technical and engineering understanding of the real-world challenges support the strategic work.

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Disclaimer

Executive Summary

Introduction

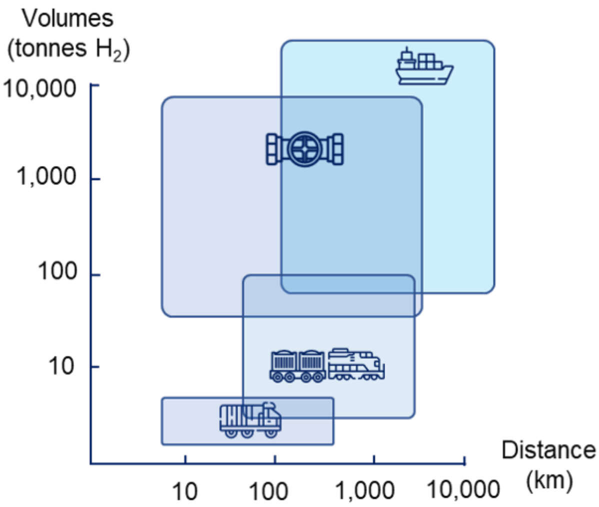
Hydrogen is an energy carrier which can be used in a vast range of applications in many energy consuming sectors. As the combustion of hydrogen is free of CO_2, deployment of low-carbon hydrogen can help economies meet their GHG emissions reduction targets. As a result, many governments are exploring the regional and national opportunities for the adoption of hydrogen in sectors such as transport, industry, power or buildings.

Hydrogen can be used as a commodity to interconnect regions and build new supply chains, where both producers and consumers benefit from the decarbonisation potential which this energy vector can bring. As with many of the currently used sources of energy, such as oil and gas, key stages in hydrogen supply chains are transportation and storage. As a commodity experiencing demand growth, it is important for regional governments to understand the different hydrogen transportation and storage options which can be employed to support this growth. Similarly, exploring how these options can be used to connect points of supply and demand, both within a region but also internationally, will help regions leverage their existing infrastructure assets, exploit trading opportunities and identify the most cost-effective pathways to support hydrogen growth.

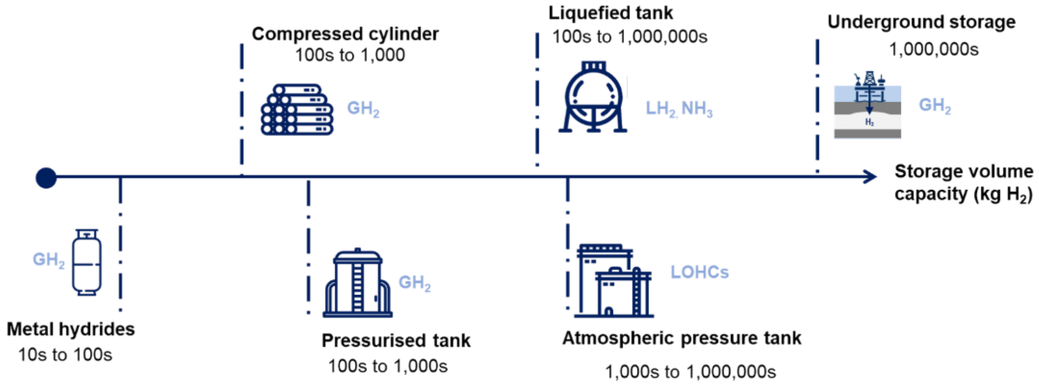
This study examines opportunities and options for the different hydrogen transportation and storage methods identified in five regions: North Rhine-Westphalia, Zuid-Holland, Hauts-de-France, Scotland and Alberta.

Options for transportation and storage of hydrogen

Hydrogen as a commodity can be transported and stored in compressed or liquefied form or can be carried as ammonia or in liquid organic hydrogen carriers (LOHCs). To transport hydrogen using these different options, trailers, trains, ships and pipelines can be used. Each of these options can transport hydrogen at different scales and distances. However, the most suitable option is context specific, depending on a series of additional factors determined by the end-use phase, such as purity or continuity of supply requirements.



As with hydrogen transportation methods, existing hydrogen storage options can accommodate a wide range of volumes, enabling both intraday and interseasonal storage of the different forms of hydrogen (compressed, liquefied, ammonia or LOHCs). Besides storage capacity, the suitability of storage options is determined by storage duration, speed of discharge and purity requirements, as well as infrastructure availability and geological resources. In order of increasing hydrogen storage capacity, the different options for storage include: metal hydrides, compressed cylinders and pressurised tanks for compressed hydrogen storage; liquefied tanks for the storage of liquefied hydrogen and ammonia; atmospheric pressure tanks to store LOHCs; and underground storage (most noticeably salt caverns) to store compressed hydrogen.



There is a large potential for hydrogen uptake in the regions considered

North Rhine-Westphalia. The region has a vast potential for the use of hydrogen across all sectors. By 2050, demand for hydrogen could comfortably exceed 100 TWh per year. Even though a large portion of the renewable electricity generation capacity could be used to produce green hydrogen locally, the region is expected to rely on imports of hydrogen from the north of Europe and from overseas. Today supply and demand are connected via hydrogen pipelines for industrial use and using trailers for transport use. However, as demand for hydrogen grows, the region can start a phased conversion of its extensive natural gas network infrastructure to help meet the region's high hydrogen demand. North Rhine-Westphalia can exploit its salt cavern facilities to store hydrogen if connected to a future pipeline system. The region can also use the Rhine river as an important waterway to transport hydrogen to industries and urban areas.

Zuid-Holland. Hydrogen in Zuid-Holland could find applications in multiple sectors, however the current focus for hydrogen uptake lies within the industrial sector for refineries and petrochemicals and in transport. The Port of Rotterdam is expected to play a central role in the regional provision of hydrogen, where centralised production of blue and green hydrogen could be located. In addition, the port can leverage its existing infrastructure to continue servicing energy exports to the rest of Europe. This could result in hydrogen transportation distances ranging from localised uses, such as in the port's industrial cluster, to large distances where hydrogen is exported to other European regions. To connect to these neighbouring demand points, repurposed hydrogen pipelines could be used. The Rhine river can also be used as a hydrogen trading corridor to connect to regions where demand is expected to grow considerably, such as North Rhine-Westphalia.

Hauts-de-France. As part of *Third Industrial Revolution Master Plan Initiative,* Hauts-de-France has recognised the role that hydrogen produced from renewable sources can play in energy storage and mobility sectors. However, blue hydrogen production is also possible, and hydrogen could find uses in steel, chemical and pharmaceutical sites within the Dunkirk industrial cluster along with smaller agricultural and glass industries dispersed around the region. Hauts-de-France is already connected to Belgium and Netherlands via hydrogen pipelines for industrial use, which could be expanded to accommodate growing hydrogen demand. There are also opportunities for shorter, regional hydrogen supply chains as additional green hydrogen generation capacity is installed in the region close to demand sources, for which trailers and trains could be used. In addition, the Seine-Nord Europe Canal project, to open in 2024, would also allow for the transhipment of hydrogen from regions with hydrogen hubs, such as the Netherlands.

Scotland. There is a large potential for hydrogen demand, with some estimates that a Scottish hydrogen economy could consume up to 90 TWh annually in 2050 (2.7 Mt H_2). The buildings sector, along with industrial sites in the Central Belt of Scotland could be important sources of demand. Both blue and green hydrogen production are possible, given the region's extensive wind and CO_2 storage resources. Blue hydrogen production can be built near gas terminal facilities or directly in industrial clusters. In contrast, green hydrogen could be produced in proximity to demand points or produced with offshore electrolysers. In a scenario where uptake of hydrogen is cross-sectoral, use of pipelines would be the most suitable option for regional distribution. Scotland can potentially become an important exporter of hydrogen, in which case shipping in the form of ammonia or LOHCs would be most cost-effective. North Rhine-Westphalia, Hauts-de-France and Zuid-Holland have been identified as potential future sources for the export of hydrogen.

Alberta. Currently, most regional hydrogen demand comes from industrial sites, where established supply chains allow for the on-site production and consumption of hydrogen, or for the hydrogen to be distributed to specific consumers. There are growth opportunities for hydrogen in the transport sector and for additional demand in industrial clusters. Alberta's *Hydrogen Strategy,* to be published in October of 2020, is aiming to provide support to produce blue hydrogen. Alberta is expected to produce both blue and green hydrogen in the long-term, but blue hydrogen production could be initiated in the Industrial Heartland. Despite the region's large dimensions, key areas for hydrogen production facilities could be located relatively near demand centres, primarily located in Southern Alberta (few 100s of km apart). Given the potential for hydrogen production, creating a market for exports would result in large transportation distances (ca. 1000km or more), to either coast of Canada, in which case pipeline transportation either as ammonia or compressed hydrogen would be most cost-effective.

Overarching hydrogen transportation recommendations

For the **transportation of large volumes of hydrogen** (in the order of kt of H_2) **over long distances** (+1,500km), **pipelines and ships** are the most suitable methods. At this scale, repurposing a natural gas transmission pipeline results in the lowest transportation costs, around a fifth of the costs of building a new hydrogen transmission system. Transportation of ammonia via pipeline shows comparable economics to those of compressed hydrogen, however their use is less advisable if the ammonia is to be reconverted to hydrogen before end-use. Conversely, the use of ships to transport hydrogen is done most cost effectively when using ammonia or LOHCs relative to LH_2 shipping, as ammonia and LOHCs shipping show similar costs over the distances considered. Even though both ammonia and LOCHs are likely to be reconverted before end-use, shipping of hydrogen in this form can be cost-effective if their reconversion is performed using centralised infrastructure in ports, as this would lower the reconversion costs relative to decentralised reconversion.

For the transportation of **medium and low volumes of hydrogen** (in the order less than a kt of H_2) at the distribution scale (less than 1,500 km), **trailers, distribution pipelines and trains** are the most suitable forms of transportation. At this scale, trains generally exhibit the lowest transportation costs of the three options, with transportation as ammonia showing the lowest costs and compressed hydrogen gas showing the highest. Trailer transportation of hydrogen would be the cheapest as ammonia or liquefied hydrogen. Even though these show similar economics, the additional reconversion step required for ammonia before end-use means that trailer transportation as liquefied hydrogen is favoured. Trailers can transport anything in between 1-5 tonnes of H_2. As demand grows (e.g. 500 tonnes of H_2 consumed per day), pipelines are more suitable to cover the transportation requirements, and at such demand scale pipelines can be used more cost effectively than trailers.

The most suitable hydrogen transportation recommendations for each region will ultimately depend on how the transportation options mentioned above integrate within the overall hydrogen supply chain choices. These supply chain options will be influenced by a multiplicity of factors, such as regional hydrogen supply and demand volumes and the distances between the different supply and demand points. More specifically to hydrogen transportation options, the existing level of regional infrastructure for rail, road, port and pipeline networks, as well as options for imports and exports, will influence the overall cost-effectiveness of transportation and storage methods. As a result, regions can use their existing natural and infrastructure assets to achieve not just lowest cost for transportation and storage but also for the entire supply chain.

Suitability of hydrogen storage technologies is context specific and depends on a variety of factors such as storage volume requirements or cyclability requirements. Large scale storage of hydrogen as **ammonia or LOHCs in tanks** could reuse existing oil and gas storage assets and show high integration in those hydrogen supply chains where imports or exports via ship occur in the form of ammonia or LOHCs. In industrial clusters, there is an opportunity for the large-scale storage of hydrogen in **liquefied** form if industrial demand for hydrogen grows sufficiently as to allow liquefaction tanks to benefit from large economies of scale. In those regions where underground storage of **hydrogen in salt caverns** is possible, there is an opportunity for this form of storage to show very competitive economics, especially if these salt caverns can exploit already existing infrastructure e.g. natural gas pipelines repurposed to transport hydrogen.

The analysis of five regions to examine the different options for hydrogen transportation and storage suggests that the presence of both sea and river ports as well as interregional natural gas pipeline infrastructure can facilitate lower transportation costs of hydrogen for exports or imports. For regional transportation, close proximity of potential hydrogen demand points and existence of multimodal transportation corridors can also lead to a wider selection of options for the cost-effective transportation of hydrogen.

Acronyms

ACTL	Alberta's Carbon Trunk Line
ATR	Autothermal reforming
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation and Storage
CO_2	Carbon Dioxide
EU	European Union
GHG	Greenhouse Gas
GH_2	Gaseous Hydrogen
H_2	Hydrogen
HGV	Heavy Goods Vehicle
HRS	Hydrogen Refuelling Station
ITP	Industry Transition Platform
km	kilometers
kt	kilotonnes
LH_2	Liquid Hydrogen
LOHCs	Liquid Organic Hydrogen Carriers
Mt	Mega tonne
POR	Port of Rotterdam
SMR	Steam methane reforming
tpd	Tonnes per day
TWh	Terawatt hour

Note on terminology

'Blue hydrogen' refers to hydrogen produced from a feedstock of natural gas by steam methane reforming (SMR) or autothermal reforming (ATR) coupled with carbon capture, utilisation, and storage (CCUS) of the resulting carbon dioxide emissions. 'Green hydrogen' refers to hydrogen produced through water electrolysis using renewable electricity.

Throughout the report, all calculations involving hydrogen energy density or calorific value have been calculated using the lower heating value (LHV).

Contents

1 Introduction

This chapter introduces the work in this report by providing an overview of the context and objectives of the study, followed by the scope of work and analysis undertaken by Element Energy.

1.1 Context

Within the Under2 Coalition, the Industry Transition Platform (ITP) works with governments from highly-industrialized regions to develop strategies to reduce industrial emissions while supporting economic growth, job creation and prosperity. The ITP have taken a particular interest in the transportation of hydrogen, both domestically and via export. Assessing such opportunities requires an understanding of hydrogen storage and transportation technologies as well as transportation routes (including transportation via rivers when possible).

The research has been tailored to the participating regional governments, including North-Rhine Westphalia (Germany), Alberta (Canada), Hauts-de-France (France), Scotland (United Kingdom) and Zuid-Holland (The Netherlands).

1.2 Objectives

To determine the suitability of the different hydrogen transportation and storage methods in the five participating regions, this study was tasked with the following objectives:

- Infrastructure requirements for the transportation and storage of hydrogen in its different forms, namely compressed hydrogen, liquefied hydrogen, ammonia and LOHCs.
- Potential pipeline routes, and repurposing potential of existing infrastructure to connect the potential points of hydrogen supply and demand. Potential shipping routes for the intraregional or interregional transportation of hydrogen to meet exports or import requirements.
- A summary of policies or programmes already available to support decarbonisation, with an emphasis on their applicability to support growth of low carbon hydrogen.
- A note on current international Covid-19 situation, especially on effect on hydrogen projects.

1.3 Scope of work and analysis

The scope of work and analysis carried out in this study can be broken down into distinct phases. A review of available literature on hydrogen storage and transportation technologies as well as hydrogen programmes and policies in the participating regions was carried out. Interviews with relevant stakeholders of each participating region were conducted to gather additional regional information.

The outputs from the research and regional data collection and stakeholder engagement step were used to assess which transport technologies are most suitable for the regions considered in this study; by evaluating factors such as where demand and production of hydrogen are expected in the future, key routes and infrastructure.

In parallel to the regional analysis outlined above, a high-level techno-economic analysis for the hydrogen transportation and storage technologies identified (see Table 1) was performed. The techno-economic analysis consisted of an evaluation of cost parameters, but also included other relevant parameters which reflect the different characteristics of each technology. These parameters include technological readiness, suitability at different scales of hydrogen transportation and storage, ramp up availability and other relevant constraints.

Outputs from the identified transportation and storage suitability options for each region were then compared using the findings from the techno-economic analysis, with the objective of providing the final hydrogen transportation and storage regional recommendations for each region.

Table 1: Hydrogen transportation and storage methods covered in the techno-economic analysis

Hydrogen or hydrogen carrier	Transportation method				Storage method
	Pipelines	Trucks	Rail	Shipping	
Compressed hydrogen (GH_2)	✓	✓	✓		Pressurised tank, compressed cylinder, tube trailer & underground storage, metal hydrides
Liquefied hydrogen (LH_2)		✓	✓	✓	Liquefied tank
Ammonia	✓	✓	✓	✓	Liquefied tank
LOHCs	✓	✓		✓	Atmospheric tank

The final step was to produce regional recommendations for each of the participating regions. The regional recommendations used the findings from the previous steps, while taking into consideration region-specific characteristics and available technologies. The recommendations focused on providing an overview of areas of high demand for hydrogen production and consumption and how these could scale with time; supportive regional programmes and policies; and suitable technologies and transportation routes and how these may change through time.

1.4 Report structure

The remainder of this report is structured into 5 chapters as follows:

Chapter 2 presents the analysis for the suitability of hydrogen transportation methods applied to each of the participating regions based on potential sources of supply and demand, and the distances between them as well as on regional policies which can encourage hydrogen production growth.

Chapter 3 compares the different hydrogen transportation and storage technologies evaluated through a high-level techno-economic analysis.

Chapter 4 provides the one-page summaries and recommendations for sustainable hydrogen transportation and storage for the participating regions and highlights commonalities between the different regions.

Chapter 5 concludes the study.

2 The potential for hydrogen in the participating regions

The potential for hydrogen production and demand in a region depends on a variety of factors such as size of industrial activities, presence of transport corridors, existing available infrastructure, and availability of renewable energy, fossil fuel and geological resources. These factors, along with the potential distances between supply and demand for hydrogen, and the hydrogen volumes to be transported between them, make certain hydrogen transportation technologies more suitable than others depending on the context.

2.1 North Rhine-Westphalia

As one of the most industrialised regions in Germany, North Rhine-Westphalia can play a pivotal role to help realise Germany's objectives outlined in the recently published *National Hydrogen Strategy*[1]. The available infrastructure and transportation connections to other industrialised regions make North Rhine-Westphalia a suitable hydrogen hub to connect points of large-scale hydrogen production and hydrogen demand.

Regional support for the build-out of hydrogen supply chains is available through funding schemes which address hydrogen technologies at the research and development, pilot, and demonstration levels[2]. Although no policies which directly encourage the roll-out of hydrogen transportation infrastructure have been implemented, the regional government has already expressed interest in cross-border collaboration, in particular with the Netherlands[3].

North-Rhine Westphalia could become one of the largest users of hydrogen in Europe

The region's industrial landscape is dominated by iron and steel sites, chemicals facilities, and refineries. These sites could become consumers of hydrogen for high temperature applications, as well as for industrial feedstock, especially sites in the Ruhr region. This is particularly true for the region's prominent steel sector, which could decarbonise by switching to direct reduction of iron using hydrogen[4]. It is estimated that total annual regional hydrogen demand from the industrial sector could be well over 100TWh in 2050 i.e. over 3Mt H_2[5]. Demand for hydrogen in the transport sector is also expected to grow as additional refuelling stations and pilot programmes continue to be implemented to kickstart hydrogen supply chains. In addition, as coal is phased out from the power sector potential opportunities exist to substitute some of this installed capacity using hydrogen.

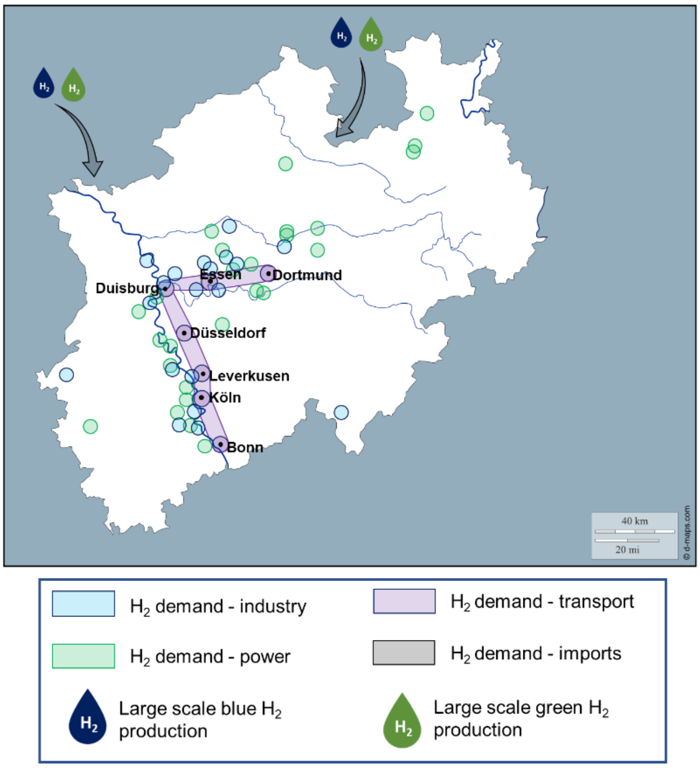


Figure 2-1: Map of North-Rhine Westphalia with potential sources of hydrogen supply and demand.

The large projections for regional hydrogen demand suggest that North Rhine-Westphalia would be expected to rely on hydrogen imports, either from regions in northern German or from neighbouring European countries such as the

[1] Federal Ministry for Economic Affairs and Energy Public Relations Division, The National Hydrogen Strategy (2020)
[2] To date, the state government of North Rhine-Westphalia and the European Regional Development Fund have provided almost € 150 million for over 140 fuel cell and hydrogen projects.
[3] In4Climate: Hydrogen as the Key to a Successful Energy Transition: Setting the Course Now (2019)
[4] The EU's largest steel site in Duisburg is aiming to convert all its blast furnaces to hydrogen in 2022.
[5] Ministry of Economic Affairs, Innovation, Digitilisation and Energy of the State of North Rhine-Westphalia: North Rhine-Westphalia Hydrogen Study, Executive Summary (2019).

Netherlands. These hydrogen imports may initially come from blue hydrogen production sites close to CO_2 storage facilities in the North Sea[6]. Imports from green hydrogen production - which is expected to be Germany's main hydrogen source are also expected to come from northern Germany. In 2050 as much as 90 TWh of electricity could be produced annually in the region for electrolysis from dedicated solar PV and wind capacity to produce green hydrogen[5].

Interregional and international transportation routes will be needed

At present, most hydrogen demand originates from industry and the existing points of supply and demand are connected either by a direct hydrogen pipeline connection or via last-mile delivery by road[7]. However, as hydrogen demand grows in different regional industrial clusters, interconnections for hydrogen transportation between clusters will become essential.

Future hydrogen supply chains for the transportation of hydrogen in North Rhine-Westphalia are expected to be extensive as multiple points of hydrogen production, consumption, and storage become connected by transportation infrastructure. This means that key supply chain routes will vary widely and range from very short lengths (of 10s of km) for decentralised generation using electrolysis, to over 100s of km in distances where hydrogen is imported.

Pipelines and shipping are the most suitable options for the transportation of hydrogen

As mentioned, industry in North Rhine-Westphalia is expected to become a major consumer of hydrogen in the medium to long term. Many industries eligible for conversion are already connected to an extensive interregional natural gas pipeline network, and their repurposing is a viable solution which could ensure very large volumes of hydrogen are delivered to different industrial clusters. In addition, reuse of the pipeline system in the medium term could facilitate the connection to large scale hydrogen storage in regional salt caverns, thus providing energy security for the use of hydrogen to industrial operators.

The use of waterways such as the Rhine river is also well suited for the transportation of hydrogen. The river allows North Rhine-Westphalia to directly source its hydrogen import requirements from oversea regions or other neighbouring regions producing green hydrogen. Further, the river is a main artery to which many large urban areas and industrial sites are already connected. Complex transhipment supply chains already exist in the river, and the use of ships to transport hydrogen to these ports presents an opportunity to develop important hydrogen value chains irrespective of the existence of a dedicated hydrogen pipeline network.

2.2 Zuid-Holland

In line with the Netherlands' objectives to reach net-zero emissions by 2050, Zuid-Holland has recognised the role hydrogen may play in the region to contribute towards climate neutrality. As stated in the region's *Hydrogen Vision and Strategy*, Zuid-Holland is currently focusing on options to use hydrogen in the mobility and industry sectors[8].

The region has implemented some policies which can support the roll-out of hydrogen generation capacity, which could consequently facilitate the roll-out of the transportation infrastructure needed to deliver fully fledged hydrogen supply chains. The SDE++ scheme, which secures the return on investment by defining a return for the investor, can be used to support CCS projects tied to blue hydrogen production[9]. Similarly, this year (2020), production of hydrogen by electrolysis is now included in the SDE++ for the first time. Another scheme, the DEI+ scheme, supports innovative pilot projects in the field of industrial hydrogen use[10].

[6] In4Climate: Hydrogen as the Key to a Successful Energy Transition: Setting the Course Now (2019)
[7] EnergieArgentur.NRW: Hydrogen – The Key to the Energy Transition (2018)
[8] Hydrogen vision and strategy: The role of hydrogen in the energy transition and circular economy in Zuid-Holland 2030 (-2050), Provincie Zuid-Holland (2020)
[9] Netherlands Enterprise Agency. Stimulation of Sustainable Energy Transition (SDE++).
[10] Dutch Government: Government Strategy on Hydrogen (2020)

The Port of Rotterdam is expected to play a central role in the production of hydrogen

Port of Rotterdam's (POR) industrial cluster is home to numerous industrial sites which could become users of hydrogen. Refineries and petrochemical sites may use hydrogen to provide high temperature heat to decarbonise their activities. Hydrogen demand in the cluster could also result from the conversion of natural gas and coal fired power plants to run partially or fully on hydrogen.

Due to the commercial availability of hydrogen fuel cell vehicles, transport corridors are a viable option to catalyse hydrogen supply chains, and these could become key sources for hydrogen demand. Great potential exists to develop corridors in the most densely populated areas and in the connecting roads between them, as well as in the various ports in the region's congested rivers.

Zuid-Holland wants to use blue hydrogen as a stepping-stone for the transition to green hydrogen and great potential exists for the centralised production of blue hydrogen in POR. The port provides an advantageous location where connections exist for future storage of CO_2 as well as to future offshore wind capacity to produce green hydrogen. It is estimated that by 2030, 1.2 Mt of hydrogen could be produced yearly in POR[11]. After this date, a growing portion of the region's hydrogen demand is expected to come from green hydrogen imports.

Zuid-Holland can set up a prominent infrastructure system for hydrogen transportation

As a result of the region's historical role as a centre for the trading of goods and energy commodities to the rest of the country and beyond, Zuid-Holland has an extensive transportation network: waterways with various ports for inland shipping, rail, and roads for movement of goods and pipelines for oil products and chemicals[12]. The distances of the region's energy supply chains thus span from the 10s of km in length for regional supply chains, to 1000s of km for import and exports. An opportunity therefore exists to ensure that the region continues to play a central role in a decarbonised future where hydrogen is an important energy vector.

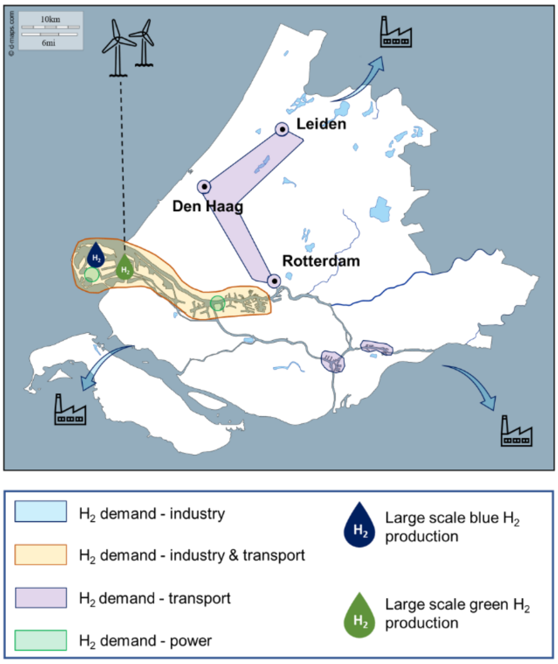


Figure 2-2: Map of Zuid-Holland with potential sources of hydrogen supply and demand.

The infrastructure available makes many transportation technologies suitable for Zuid-Holland

Zuid-Holland's wide range of routes along with its pivotal logistical role imply that hydrogen could be transported cost-effectively between regions of production and consumption. However, the region's objectives to kickstart the uptake of hydrogen in the near-term implies that maturity of currently available hydrogen transportation options and existing infrastructure options become essential factors to consider.

Zuid-Holland has a complex network of natural gas pipelines which connect the region with points of natural gas production and with industrial clusters in neighbouring regions[13]. As demand for natural gas decreases – and subsequently supply – some of these pipelines will become eligible for conversion to hydrogen.

While this network is repurposed, Zuid-Holland's rail and road infrastructure could be used to directly link hydrogen production with specific consumption sites. Finally, important waterways such as the Rhine river can be used to for the transhipment of hydrogen over long distances, either imported from overseas, or from

[11] Smart Port Position Paper: Rotterdam Hydrogen Hub
[12] Port of Rotterdam Authority: New pipelines needed between Rotterdam, Chemelot and Nord Rhine-Westphalia for the energy transition (2020).
[13] As mentioned in "Port of Rotterdam: Hydrogen Economy in Rotterdam Start with Backbone (2020)", gas grid operator Gasuine is developing a plan for an open access hydrogen grid available by 2030, which will connect some of these industrial clusters.

regional centralised hydrogen production. Ports are already present at many locations in the Rhine, implying that numerous hydrogen bunker locations could be retrofitted based on existing infrastructure.

2.3 Hauts-de-France

As part of the region's objectives to meet all energy demands from renewable energy sources by 2050, Hauts-de-France has recognised the value which hydrogen can bring to its economy. The *Third Industrial Revolution Master Plan Initiative* (REV3) states that hydrogen can play a role in both storage of energy and mobility, with a focus on hydrogen from renewable sources[14]. Nevertheless, potential for hydrogen goes beyond these areas.

Hydrogen generation currently receives support for growth through various means. Regional programmes have encouraged the uptake of hydrogen generation, especially in the mobility sector[15]. At the national level, France has a carbon tax on fossil fuel frozen at 44.60€ per tonne of CO_2 (as of 2020). In addition to the REV3 initiative, Hauts-de-France has implemented a regional hydrogen action plan aiming to support the growth of local hydrogen production chains as well as encourage the uptake of hydrogen in different sectors[16].

Demand for hydrogen could be largely spread around the region

The Dunkirk industrial cluster holds a large potential for the consumption of hydrogen demand in the future: both for feedstock and for high temperature hydrogen industrial applications. The cluster is home to a steel site and chemical, pharmaceutical, and metallurgy sites. Other potential industrial sources of demand could be smaller industrial sites in the agri-food industry and glass manufacturing sites[16]. In addition, production of synthetic methane via methanation of hydrogen using CO_2 could also constitute an important hydrogen demand source[17]. The region also has a large potential for the uptake of hydrogen in the transport sector. Hauts-de-France has an intense road transport transit, as the region serves as a European logistics hub (especially the area around Lille). A high source of hydrogen demand could potentially come from heavy goods vehicles. Similarly, the use of hydrogen in the shipping sector could grow following the 2024 opening of the Seine-Nord Europe river canal, which will connect Hauts-de-France with other regions likely to seek hydrogen uses for ships in their waterways. Demand for hydrogen from light duty vehicles should also be expected as cities become more conscious of urban pollution.

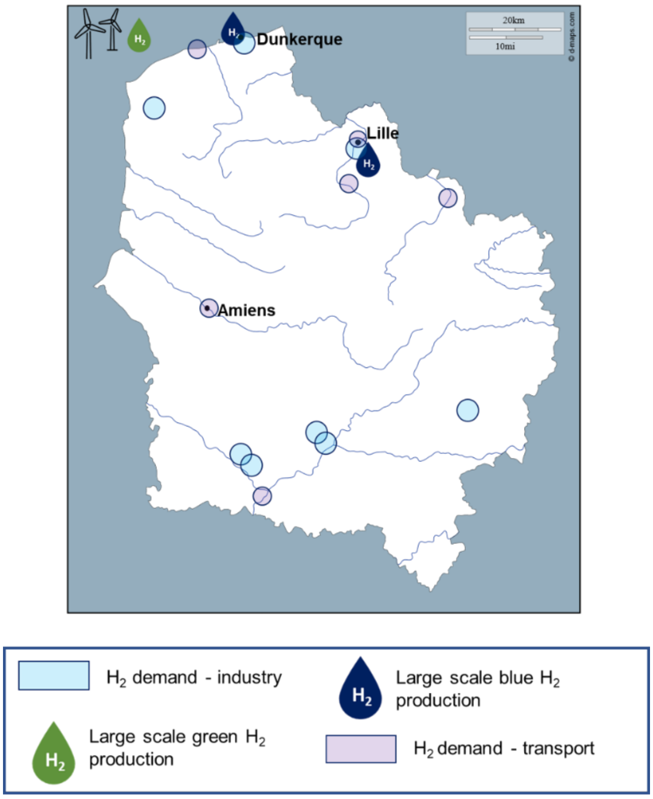


Figure 2-3: Map of Hauts-de-France with potential sources of hydrogen supply and demand.

Hydrogen demand in the transport sector has so far been met via decentralised or semi-centralised green hydrogen production using grid electricity or by importing hydrogen via pipeline from Belgium. Centralised production of green hydrogen could be commissioned if Hauts-de-France exploits its offshore wind capacity. Because the region's power grid is already decarbonised, additional centralised production of green hydrogen can be commissioned[18]. Subject to CO_2 transportation and storage network or port availability, the region has

[14] Région Hauts-de-France: Rev3, La 3[ere] Révolution Industrielle En Hauts-de-France, based on Jeremy Rifkin's Third Industrial Revolution (2011).
[15] See Storengy Project and hydrogen buses by the Artois Gohelle transport authority.
[16] Région Hauts-de-France, Towards the Development of carbon-free hydrogen in Hauts-de-France (2020)
[17] Methanation is a reaction by which CO_2 is reacted with hydrogen to produce methane and water.
[18] The H2V INDUSTRY construction of 5 100MW green hydrogen production facilities in Dunkirk could be used to meet demand in oil and chemical industries, in the mobility sector and in potential gas infrastructure blending.

a lot of potential for blue hydrogen production, as Hauts-de-France imports large amounts of natural gas and has substantial storage capacity for natural gas in aquifers[19]. Finally, high purity hydrogen produced as a by-product from certain industrial processes such as chlorine could be recycled and used locally.

Regional use of hydrogen could result in a wide range of hydrogen transportation distances

The dispersed location of industrial sites throughout the region and expected growth of hydrogen demand in refuelling stations constitute an opportunity for some hydrogen production to be green and decentralised, resulting in short transportation distance requirements with relatively low volumes. Additionally, Hauts-de-France can use the existing hydrogen pipeline network connecting the region with Belgium and the Netherlands to further increase hydrogen transportation. In addition to pipeline use, import connections to future hydrogen valleys in Belgium, Germany and Netherlands could be serviced also by ships, resulting in transportation distances of a few hundred kms. Even further distances for the transportation of hydrogen could be materialised if the Dunkirk port were further developed to service long-distance hydrogen imports.

The connections to potential production sources allow for various transportation options

Due to the region's importance as an interregional transport corridor, Hauts-de-France has a complex transport network e.g. rivers, sea, rail and road transport. Additionally, the region already has experience in the interregional transport of hydrogen via pipeline. As such, many methods are suitable for the transportation of hydrogen. The best combination and selection will ultimately depend on the size of the different hydrogen value chains.

If hydrogen demand were mostly to come from hydrogen refuelling stations (HRSs) for the transport sector, trailer and rail delivery would probably be sufficient to deliver the required volumes between decentralised sources of production and the dispersed HRSs.

A major uptake of hydrogen in industry would require larger transportation volumes, and most likely longer transportation distances to access storage sites whilst also connecting to centralised hydrogen production sources. Regardless of the final distances needed, pipelines would be the most suitable transportation method, irrespective of hydrogen being imported or being produced locally in industrial sites. New pipelines could be built and the existing hydrogen pipeline network expanded, or natural gas pipelines repurposed. However, the region's role as a national provider of natural gas storage could result in a combination of both new and repurposed options needed, for instance, if Hauts-de-France continues to supply natural gas to sites producing blue hydrogen.

Use of ships to transport hydrogen would allow the region to create flexible hydrogen trade routes with other European regions. It could enable the region to fulfil its long-term ambitions to utilise green hydrogen by mostly importing hydrogen from long-distance oversea regions where it can be produced cheaply.

2.4 Scotland

Scotland has set out ambitious decarbonisation goals, aiming to transition to net-zero by 2045, five years earlier than the UK's net-zero target. The region has rich wind and geological resources in the North Sea, and these can be exploited for the large-scale production of both green and blue hydrogen. In addition to helping Scotland decarbonise, leveraging these extensive resources presents an opportunity for Scotland to become an important exporter of hydrogen to other regions of the UK as well as overseas.

Regional support to encourage the generation of hydrogen has so far come in the form of funding for specific demonstration projects in the transport sector, as well as the creation of small-scale hydrogen supply chains using decentralised green hydrogen production[20]. As part of Scotland's wider decarbonisation strategy, the Climate Change Plan's Third Report on Proposals and Policies 2018-2032 states that policy developments

[19] The DMX demonstration project in Dunkirk, to start operations in 2025, will capture approximately 1 $MtCO_2$ annually from a steel-making plant, where the CO_2 will be shipped and stored in the North Sea.
[20] Scottish Government, Support for Hydrogen and Fuel Cells

are needed to support emerging hydrogen opportunities, such as continuing to investigate the use of hydrogen in the transport sector or hydrogen injection into the gas grid[21].

Scotland has potential for the regional production of both blue and green hydrogen

There is a large potential for hydrogen demand in Scotland. A study estimated that a major uptake of hydrogen throughout all sectors of the Scottish economy could result in approximately 90 TWh (2.7 Mt H_2) of hydrogen being consumed annually in 2050[22]. The buildings sector in high population density areas could become a major source of hydrogen demand, along with industrial sites in the Central Belt of Scotland as well as dispersed distilleries. The Grangemouth industrial cluster alone could see important demand for hydrogen for fuel switching from a refinery site, chemical, pharmaceutical sites, and glass sites[23].

Production of hydrogen is expected to be both in the form of blue and green hydrogen, given the region's access to North Sea offshore wind resources and CO_2 storage fields. Blue hydrogen production is expected to be built in locations where large volumes of natural gas can be delivered, such as gas terminal facilities, or industrial clusters. In contrast, green hydrogen could be produced in proximity to demand points, in coastal areas of the north east or directly produced offshore with offshore electrolysers. Finally, use of hydrogen in remote areas of Scotland could be in the form of decentralised green hydrogen production.

Distances between supply and demand for hydrogen in Scotland could vary considerably

The potential location of sources for regional hydrogen supply and demand suggest that Scotland's transportation infrastructure could require long distances to be covered, where transportation of large volumes of hydrogen is carried out from north to south (ca. 200 kms). This already happens with natural gas, due to the region's traditional role as a net provider of energy to the wider UK, meaning that there is already an extensive network of natural gas pipelines.

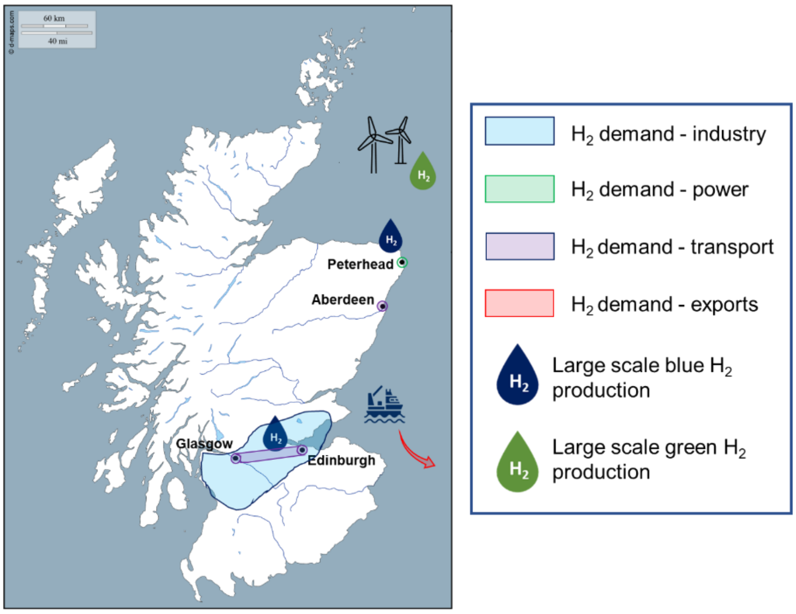


Figure 2-4: Map of Scotland with potential sources of hydrogen supply and demand.

Regarding exports via shipping, the overall infrastructure requirements would depend on the total demand to be exported, varying from shorter distances to meet national demand, to very high distances to access global markets. However, the expected growth for hydrogen demand in continental Europe means that transportation distances could be close to 1000 km, particularly if supplying to the northern European market.

Suitability of transportation options largely depends on final demand volumes

The most suitable form of hydrogen transportation would depend on the final volumes of hydrogen to be consumed: either regionally or for exports. If transportation requirements are very high (in the 10s of kt scale) then pipelines - either new or repurposed - are the most suitable option as these would allow blue hydrogen production facilities to run at high utilisation rates. If the Scottish building sector were to convert to the use of hydrogen, then transportation by pipeline may be the only economically sound form of hydrogen transportation.

[21] Scottish Government, Climate Change Plan: The Third Report on Proposals and Policies 2018-2032 (2018)
[22] Scottish Government, Scottish Energy Strategy: The Future of Energy in Scotland (2017)
[23] A recent report prepared by Element Energy for Pale Blue Dot Energy estimated this annual hydrogen demand to be of 7 TWh. Hydrogen in Scotland: The Role of Acorn Hydrogen in Enabling UK Net Zero (2020).

Additionally, the use of pipelines would also facilitate a strong growth of hydrogen supply chain for exports, by establishing direct connections between production sites and ports. Scotland has a number of ports where hydrogen supply chains can be established. However, lead times would become a challenge, as long-distance exports would probably require some of this port infrastructure to be further developed, both in terms of space available for storage of hydrogen as well as for higher deadweight ship allowance.

In a scenario where demand for hydrogen is spread and used only for specific applications, such as HRSs or in distilleries, then hydrogen transportation could be performed using trains or trailers, as delivering hydrogen from centralised hydrogen sources by pipeline could become prohibitive.

2.5 Alberta

Alberta's large oil and gas resources, as well as its potential for renewable energy generation, present a promising opportunity for the region to become a leader in Canada to produce hydrogen. The region-wide adoption of blue hydrogen would allow Alberta to find alternative uses for its fossil resources while Canada transitions to net-zero by 2050.

Alberta has implemented various regional policies which can encourage the uptake of hydrogen. The region has a carbon tax for large industrial emitters, taxed at $30 per tonne of CO_2 (as of 2020), and raising $10 every year until 2022. Additionally, legislated limits on oil sands emissions have encouraged new research and development activities to extract hydrogen from oil, gas, and oil sands reservoirs while leaving behind the CO_2[24]. To support the case for hydrogen growth in Alberta, the regional government is planning to announce a *Hydrogen Strategy* in October of 2020, which will aim to provide support to produce blue hydrogen[25].

Hydrogen use could grow in the industrial, power and transport sectors

Most of the current hydrogen demand in Alberta comes from industrial sites, where established hydrogen supply chains exist locally to produce and consume hydrogen on-site, or to distribute the hydrogen to specific consumers such as refining complexes and fertilizer manufacturing sites[26]. Thus, the region already produces large amounts of hydrogen in oil and gas, chemicals, and petrochemical sites mostly for consumption in Edmonton's Industrial Heartland industrial cluster[27]. There is potential for additional hydrogen demand from industry, not just in Alberta's industrial cluster but also in Alberta's dispersed fractionation sites for high temperature applications. In addition, there are growth opportunities for the uptake of hydrogen in the transport sector, where the scale of use is currently very small[28]. This is because the region has a large sector for the long-distance transportation of heavy goods, for which hydrogen fuelled trucks are highly suitable.

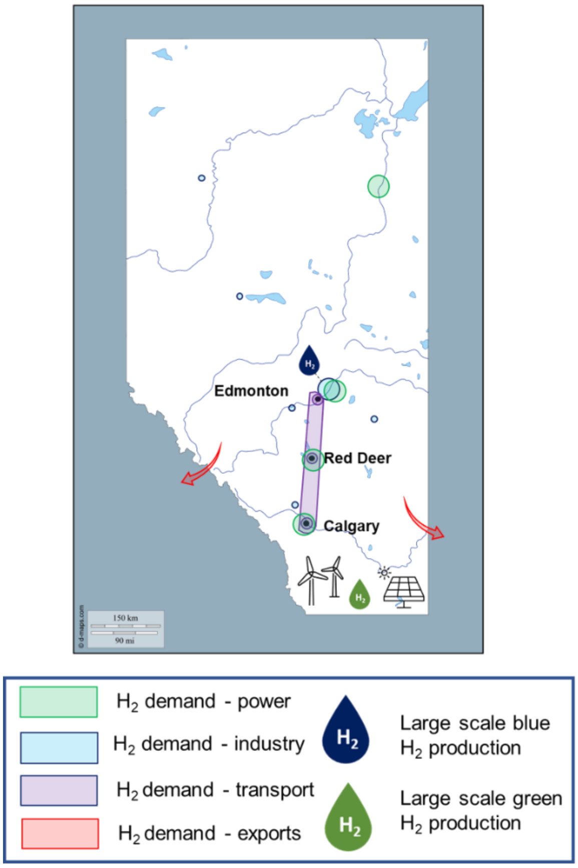


Figure 2-5: Map of Alberta with potential sources of hydrogen supply and demand.

Alberta is expected to produce both blue and green hydrogen in the long-term. Relative to other markets, Alberta can produce blue hydrogen in a cost-effective

[24] Phys.org, Scientists Extract Hydrogen Gas from Oil and Bitumen, Giving Potential Pollution-Free Energy (2019)
[25] The Fort Saskatchewan Blending Project pilot project which aims to add a blend of 5% by volume to the natural gas supply for 5,000 household will start early next year
[26] City of Edmonton, Urban Form and Corporate Strategic Development, Role of Alternative Fuels (2019)
[27] Alberta currently produces 1.8 Mt of hydrogen annually, an important amount of Canada's 3 Mt hydrogen production.
[28] Energy Futures Lab, Building an Albertan Hydrogen Economy (2020)

manner. Blue hydrogen production could be initiated in Alberta's Industrial Heartland, as the recent inauguration of Alberta's Carbon Trunk Line which transports CO_2 for storage has sufficient additional capacity to transport CO_2 emissions from blue hydrogen[29].

In addition, the region has an abundance of untapped wind and solar PV resources which can be used for the centralised production of green hydrogen. Use of hydrogen in the power sector could also occur as the region phases out coal by 2030. However, there may be competition for the use of this renewable energy in the power sector as currently, Alberta still relies heavily on fossil fuels for the production of electricity.

Production of hydrogen could be centred in southern Alberta

Despite Alberta's large dimensions, key areas for hydrogen production facilities could be located relatively near demand centres, which are primarily located in southern Alberta (few 100s of km apart). Large amounts of natural gas arriving near Edmonton could be reformed to meet industrial hydrogen demands. Similarly, wind and solar PV resources are also located in the southern part of the region, which is the most densely populated area of Alberta. Therefore, distances between areas of production and consumption of hydrogen would be in the few 100s of km. Given its large potential for regional hydrogen production, if Alberta aimed to create a market for hydrogen exports, transportation would be in the 1000s of km, to either coast of Canada. However, the infrastructure is not currently available, as all existing hydrogen pipelines are within Albertan borders.

Use of trailers and rail for the delivery of hydrogen for transport to catalyse demand

The current hydrogen transportation methods used in Alberta, where hydrogen is delivered to specific industrial consumers, suggests that there is no common market for the cross sectoral use of hydrogen beyond industry. As such, new transportation infrastructure would be needed as hydrogen demand grows. The creation of transport corridors between large urban areas and around industrial clusters could be a good starting point to kickstart an initial demand for hydrogen. The hydrogen refuelling infrastructure could then be supplied with hydrogen being transported by rail or trailer from centralised sources of production. As demand continues to grow, new hydrogen pipelines connecting to refuelling stations could become more cost-effective.

The long distances needed to export hydrogen would probably require the commissioning of new hydrogen transmission pipelines, as the current pipeline network used for natural gas is expected to continue in operation for the transportation to industrial sites and exports[30].

[29] See additional information on Alberta's Carbon Trunk Line (ACTL) here. The ACTL is considered to be the backbone needed to achieve a lower carbon economy in Alberta. It is the world's largest capacity pipeline for CO_2 transportation, it can transport up to 14.6 Mt of CO_2 per year. This is the amount of CO_2 emitted by 2.6 million cars in Alberta.

[30] Planning for new hydrogen pipeline routes, whether for regional delivery or for exports, will need to be sensitive to indigenous land borders.

3 Overview of hydrogen transportation and storage technologies

In hydrogen value chains, hydrogen can be found in compressed/liquefied form, as ammonia or as a liquid organic hydrogen carriers (LOHCs). As represented in Figure 3-1, many options exist to transport and store these different hydrogen archetypes and because there are technologies to convert the hydrogen from one archetype to another are available, hydrogen value chains have the potential to be highly interchangeable.

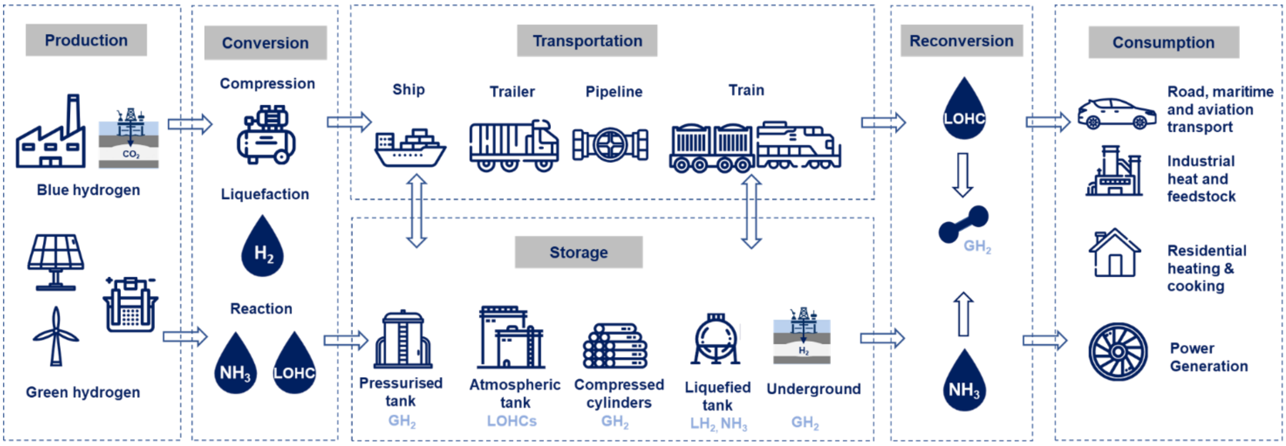


Figure 3-1: Schematic overview of the different stages in the supply chain for hydrogen and archetypes. A stage for reconversion to hydrogen before end use applications can be optional.

Due to the flexibility of the different value chains and their variety of options, it is important to understand which options for transportation and storage provide the best value and are most suited for a specific end use. This Chapter provides a techno-economic analysis for the different hydrogen storage and transportation technologies identified. Although additional options exist, this study focuses on technologies with commercial products clearly visible in development and whose direct use does not result in CO_2 emissions[31].

3.1 Description of hydrogen transportation and storage technologies

Prior to the transportation and storage stage, emissions-free production of hydrogen can be performed as blue hydrogen - where fossil fuels are used and their emissions abated with a carbon capture technology – or as green hydrogen, where electrolysis of water into hydrogen and oxygen is powered using a renewable source of electricity.

Once the hydrogen is produced, it is optionally converted to a form suitable for either transportation or storage. This stage may involve the compression or liquefaction of the hydrogen gas or, alternatively, its conversion to ammonia via reaction with nitrogen or to LOHCs via a hydrogenation step.

Different hydrogen archetypes

Hydrogen H_2 **-**

In its pure gaseous state, hydrogen has a low energy density relative to conventional energy carriers, such as gasoline or ethanol. Nevertheless, higher energy densities are possible if the hydrogen is compressed (GH_2) or liquefied (LH_2), with the latter form resulting in energy densities comparable to that of natural gas at 250 bar[32]. Transporting and storing hydrogen as GH_2 or LH_2 has the advantage of providing a high-purity stream of hydrogen which is readily usable for end applications. Compression of GH_2 to 350-700 bar results in a 5-20% energy penalty, whereas liquefaction leads to a 30-40% energy penalty[33]. However, state of the art liquefaction plants can achieve energy penalties of around 18% using new liquefaction concepts, for production volumes

[31] Methanol, albeit considered as a commodity compatible with a hydrogen economy, is not investigated in this study as its dehydrogenation results in the production of CO_2 emissions. For similar reasons, investigation of blending of hydrogen with natural gas is limited to a technical description of this transportation method.
[32] LH_2 has an energy density 2.4 kWh/litre (LHV), whereas GH_2 at 700 bar has an energy density of 0.8 kWh/litre (LHV).
[33] Based on LHV, from Trevor Letcher, Storing Energy with Special Reference to Renewable Energy Sources (2016)

between 50-150 tpd[34]. Conventional plants can liquefy 5 tpd, but increasing these capacities to 50-150 tpd could exploit economies of scale and result in liquefaction costs dropping by two thirds third.

Ammonia - Ammonia

Ammonia, NH_3, is a promising liquid hydrogen carrier due to its high volumetric hydrogen density[35,36]. The synthesis of ammonia, its handling, and transportation are mature processes. Even though ammonia can be used directly in internal combustion engines, fuel cells and in turbines for power generation, none of these applications have found wide commercial acceptance[37]. Nevertheless, ammonia can be reconverted to hydrogen, but energy requirements and purity in the reconversion process are current challenges to be addressed, and the reconversion costs are highly linked with purity requirements. The conversion and reconversion of ammonia to hydrogen lead to energy penalties (LHV) of 7-18% and below 20%, respectively[38]. A study suggests that by 2040, improvements in ammonia synthesis processes and reconversion technology, as well as economies of scale could potentially reduce conversion and reconversion costs by 60% and 70% from current costs, respectively[39].

LOHCs - LOHCs

Liquid organic hydrogen carriers (LOHCs) are molecules which can be loaded and unloaded with hydrogen via a hydrogenation and dehydrogenation process, respectively. Many types of LOHCs exist, and the variants which have received most attention include methylcyclohexane, dibenzyltoluene and N-ethylcarbazole[40]. LOHCs offer improved safety, but their volumetric hydrogen density is lower than that of ammonia. Reconversion costs are strongly correlated with purity requirements, and hydrogenation and dehydrogenation of LOHCs lead to a range of energy penalties[41]. LOHCs can be used as a combustion source, but they are more expensive than conventional combustion fuels and doing so would release CO_2[42]. Once LOHCs are dehydrogenated to extract the hydrogen for use, the dehydrated LOHCs have to be returned back to the point of origin. By 2040, improvements in LOHC dehydrogenation performance, improved utilisation of hydrogenation process heat as well as upscaling could potentially reduce LOHC conversion and reconversion costs by 90% and 50% from current costs, respectively[39].

Hydrogen transportation technologies

Pipeline - H_2 LOHCs Ammonia

Pipelines can transport both liquids and gases and, depending the pipeline size and ability to operate over a range of pressures, they can regulate the flow to balance supply and demand. Despite requiring high levels of initial investment, pipelines can enable large scale growth of hydrogen. In addition, due to its low marginal operational expenditure relative to total expenditure, the economics of pipelines improve as hydrogen demand increases. Pipelines can be used as an interoperable network interconnecting multiple producers and consumers. However, pipelines require substantial planning, especially if crossing environmentally protected or high-density areas.

Currently, most dedicated hydrogen pipelines are operated by hydrogen producers in industrial clusters to deliver feedstock to chemical sites and refineries. Similarly, pipelines have been used to deliver ammonia to the fertiliser, and oil and gas industries for decades. Pipelines to transport LOHCs can reuse gasoline and diesel infrastructure. Nevertheless, once LOHCs are dehydrogenated to release the hydrogen, the carrier

[34] Cardella, U., L. Decker, and H. Klein. "Economically viable large-scale hydrogen liquefaction." IOP conference series: materials science and engineering. Vol. 171. No. 1. IOP Publishing, 2017.
[35] Volumetric hydrogen density is measured as the mass of hydrogen per unit volume of hydrogen carrier i.e. kg of H_2 per m^3 of hydrogen carrier. The higher the volumetric hydrogen density, the more usable energy the hydrogen carrier contains.
[36] Ammonia has an energy density of 3.5 kWh/l (LHV).
[37] Aziz et al. Ammonia as Effective Hydrogen Storage: A Review on Production, Storage and Utilisation (2020)
[38] IEA, The Future of Hydrogen (2019)
[39] ERIA (2019), 'The Potential and Costs of Hydrogen Supply', in Kimura, S. and Y. Li (eds.), Demand and Supply Potential of Hydrogen Energy in East Asia, ERIA Research Project Report FY2018 no.01, Jakarta: ERIA, pp.140-183.
[40] Andersson and Grönkvist, Large-scale storage of hydrogen (2019)
[41] A wide range of energy penalties are possible for reconversion of LOHCs, varying depending on LOHC molecule and technology developments for reconversion. Energy penalties (LHV) as low as 25% to 40% have been reported.
[42] Hank et al., Energy Efficiency and Economic Assessment of Imported Energy Carriers Based on Renewable Electricity (2020)

molecules need to be transported back to the hydrogenation site. This reduces the practicality of using pipelines to transport LOHCs.

Hydrogen can also be blended in small volumes with natural gas. Blending can be used as a stepping-stone to roll-out hydrogen production, as blending small percentages of up to 20% v/v hydrogen does not impact most energy consuming sectors, such as the buildings sector. Different countries have different blending standards which are usually imposed for quality and safety purposes.

Trailer - H_2 LOHCs Ammonia

Transportation of hydrogen using trailers as GH_2 in compressed gas cylinders or LH_2 using cryogenic liquid tankers is already commercially available[43]. The majority of GH_2 cylinders are made of steel, although the heavy weight of the material leads to reduced hydrogen loading volumes. Innovative composite cylinder materials allow for a higher kg H_2/litre ratio, as these materials are not only lighter but also allow for higher compression pressures. Transport of hydrogen via trailer as GH_2 or LH_2 is a well proven technology.

Ammonia and LOHCs can also be transported in trailers, and their use can potentially increase the nominal amount of hydrogen carried in every trailer. Delivery of ammonia by trailer is currently done in the fertiliser and agriculture industry. Similarly, LOHCs can employ common steel tanks used in the transport of diesel and gasoline[44].

This form of transportation is best suited for small quantities and for short distances where demand is geographically dispersed, as trailers can vary their endpoints and routes. Trailers are widely used to deliver continuous hydrogen supply for mobility applications. This form of transportation allows users to have back-up storage by planning for deliveries of hydrogen cylinders.

Train - H_2 LOHCs Ammonia

Trains can transport hydrogen in a similar way to road trailers i.e. GH_2 in pressurised tubes and LH_2 in cryogenic tanks, albeit larger transportation volumes are achievable. For instance, relative to trailer transportation, one rail tank car of ammonia can transport as much as four times more hydrogen. Similar to ships, LOHCs and ammonia can reuse existing train transportation infrastructure.

Use of trains for transportation is limited to deliveries where rail infrastructure exists, but their use allows cost-effective transport of hydrogen over longer distances relative to trailers. However, the costs incurred when hydrogen is liquefied or in the conversion and reconversion stage of ammonia and LOHCs implies that large transportation volumes are required to ensure that the overall supply chain costs benefit from economies of scale.

Ship - H_2 LOHCs Ammonia

This form of transportation can enable global hydrogen supply chains to develop, creating hydrogen production markets between areas where hydrogen can be produced cheaply with areas of high hydrogen demand. Ships can carry very large volumes, but their use may require the redevelopment of port infrastructure.

Shipping of LH_2 is currently at the demonstration stage of commercialisation. Further developments in port and storage infrastructure are needed[37]. Nevertheless, it is estimated that a significant scale-up in global shipping supply chains for LH_2 could see their cost fall by 90% by 2030[45].

Ammonia and LOHCs can leverage existing infrastructure for transport. While the former can use existing chemical and semi-refrigerated liquefied petroleum gas or propane tankers, the latter can use existing oil tankers[41]. However, LOHCs would require the return of the carrier to the port of origin.

Hydrogen storage technologies

Underground storage - H_2

[43] Hydrogen Europe, Hydrogen Transport & Distribution (2017)
[44] Reuss et al., Seasonal Storage and Alternative Carriers: A flexible Hydrogen Supply Chain Model (2017)
[45] Hydrogen Council, Path to hydrogen Competitiveness: A cost Perspective (2020)

Underground storage options include salt caverns, depleted oil and gas fields, aquifers and rock caverns. All underground storage options can hold large amounts of hydrogen and can therefore serve as hydrogen sinks for interseasonal storage. Operation of hydrogen underground storage is similar to underground storage of natural gas.

Salt caverns are the most promising option for underground storage, as hydrogen purity is not compromised. Salt caverns are artificially constructed cavities and are highly-gas tight and require less base gas that the other underground storage options. They can have high discharge rates, making them suitable for use in the industrial and power sector.

Whereas salt caverns and hard rock caverns may be cycled multiple times annually, aquifers and depleted oil and gas reservoirs may only be cycles once or twice annually, implying that the two latter options may only be compatible with hydrogen interseasonal storage[46].

Atmospheric pressure tanks - LOHCs

LOHCs can be safely stored in atmospheric pressure tanks. The storage compatibility with existing oil and gas storage tanks means that LOHCs can potentially be stored in sites where energy supply chains already exist, such as ports with oil and gas terminals, and industrial sites hosting refining and petrochemical complexes. Storage in tanks allows for the long-term, large scale storage of hydrogen without requiring intensive capital and operational expenditures. Relative to underground storage, storage tanks offer added flexibility and readiness for onward transportation[47].

Liquefied tank - H_2 Ammonia

Storage of hydrogen in liquefied form is a well-established storage option. LH_2 tanks can store more hydrogen per unit volume than GH_2 tanks and yield very pure streams of hydrogen, making them very suitable for use in HRSs. Liquefied tanks and liquefaction equipment are costly, however storage as LH_2 is favoured by economies of scale and is therefore most appropriate for large-scale storage. Nevertheless, LH_2 daily losses due to boil off are around 0.3%[41]. Unless the hydrogen boil off is used, for instance, to power a fuel cell, the long-term storage of hydrogen using this option could result in important cumulative losses. In addition, due to the pressures employed, high safety requirements are needed.

Pressurised tank & compressed cylinders – H_2

The use of pressurised tanks and compressed cylinders for the storage of GH_2 are well-established technologies and are currently the most common form of storage in HRSs. These forms of storage are recommended for intra-day stationary storage applications in small-scale uses where hydrogen needs to be readily available[41]. Underground pressurised tanks can be constructed too, making them safe options for the urban storage of hydrogen. Most marketed options are made of steel which allow for compression pressures of up to 200 bar. However, composite tanks can store up to 700 bar, but reaching these pressures incurs a more energy intensive process.

Metal hydrides - H_2

Metal hydrides store hydrogen by breaking down hydrogen molecules and by having the individual hydrogen atoms form bonds with the metal hydride. More renowned metal hydrides include magnesium hydride and aluminium hydride. Metal hydrides have been used for the storage of hydrogen in niche applications where storage weight is not a primary issue, including forklifts, submarines and scooters. However, technology advancements are needed, as metal hydrides display limited reversibility, decomposition of the storage material as well as slow reaction kinetics. The slow reaction kinetics limits the potential for use of metal hydrides in the transport sector, as high-speed hydration is needed. To reach early commercialisation of

[46] Sandia National Laboratories, A Life Cycle Cost Analysis Framework for Geologic Storage of Hydrogen (2011)
[47] The Royal Society, Ammonia: Zero-Carbon Fertiliser, Fuel and Energy Storage (2020)

advanced options for metal hydrides, there needs to be a higher focus on process capability, facilities and manufacturing planning[48].

Comparison of different hydrogen transportation and storage methods

Suitability of the different hydrogen transportation and storage options is ultimately subject to key performance parameters such as technology cost-effectiveness, technology maturity level, suitability at different scales and ramp up availability (supply chain integration). Table 2 below provides a concise comparison between the different hydrogen transportation and storage methods.

Table 2: Technology analysis of the different transportation and storage options[49].

	GH_2	LH_2	Ammonia	LOHCs	Metal Hydrides
Supply chain integration	High	High/Medium	High	Medium	Medium-Low
Transportation TRL	Ship: High Pipeline: High Train: High Truck: High	Ship: Medium Pipeline: High Train: High Truck: High	Ship: High Pipeline: High Train: High Truck: High	Ship: High Pipeline: Medium Train: Medium Truck: High	Truck: Low Train: Low
Storage TRL	Tank: High Tubes: High Underground: Medium	Tank: High	Tank: High	Tank: High	Tank: Medium
Transportation suitability at different scales	Pipeline: 10s kt Truck: 1 t	Ship: 90 t Truck: 4 t	Pipeline and ship: 10s kt Truck: 3 t	Pipeline and ship: 10s kt Truck: 2 t	Truck: 100s kg
Storage suitability at different scales	Cavern: 10 kt Tank: 1 t	Tank: 5 t	Tank: 30 kt	Tank: 80 kt (18kt H_2)	Tank: 10s kg

3.2 Economic assessment of transportation and storage methods

The transportation methods have been divided based on suitability for different transportation distances into long-distance, medium-distance, and last mile delivery. Similarly, hydrogen storage options have been divided into interseasonal and intra-day storages. When comparing transportation and storage methods, it is important to consider whole supply chain costs as well as the volumes of hydrogen which can be transported or stored by each technology, as these can vary considerably between different value chains.

All costs are reported in 2020 USD. Costs outside the scope of this study include production and purification costs for all hydrogen archetypes i.e. GH_2, LH_2, ammonia, and LOHCs. In addition, liquefaction costs as well as reconversion costs for ammonia and LOHCs are not included.

Although costs are very context specific, once hydrogen is produced, liquefaction costs stand at approximately \$1.0 per kg H_2 whereas converting hydrogen to ammonia or LOHCs costs \$1.0 and \$0.4 per kg H_2, respectively[50,51]. If ammonia or LOHCs are reconverted back to hydrogen in central facilities for final use, this adds \$0.75 and \$1.0 per kg H_2, respectively.

Transportation of hydrogen over long distances

Transportation over long distances (500km to +3,000 km) is justified for transportation methods which can deliver very high volumes of hydrogen: namely transmission pipelines and ships.

[48] Ronnebro, Ewa. *Technology and Manufacturing Readiness of Early Market Motive and Non-Motive Hydrogen Storage Technologies for Fuel Cell Applications*. No. PNNL-21473. Pacific Northwest National Lab.(PNNL), Richland, WA (United States), 2012.
[49] High=proven and commercial; medium=prototype demonstrated; low=validated or under development.
[50] These costs are indicative. Overall supply chain costs (including individual cost elements such as conversion, transportation etc.) are dependent upon scale.
[51] IEA, The Future of Hydrogen: Assumptions (2019). Installed liquefaction capacity of 700 tpd of H_2. Assumed conversion and reconversion capacities are 4,000 tpd of ammonia 11,000 tpd of LOHC.

Because of the low energy density of GH_2, shipping of GH_2 is not considered as it is not economic unless the hydrogen is in liquid form[52]. It is noteworthy to mention that the costs provided for pipeline transportation are estimated for onshore pipelines. For reference, and as a rule of thumb, construction of offshore natural gas pipelines is approximately twice the price relative to onshore pipelines[53].

Important cost factors for pipelines and ships are the distance and transport volume requirements[54]. For both transportation options, the transportation costs increase with distance. For the distance and volume scales considered in this study, pipeline costs are more sensitive to increasing distances than ships, as the longer the pipeline the more compressors or pumps are required. In ships, the increase of transportation costs with distance results from the fuel costs.

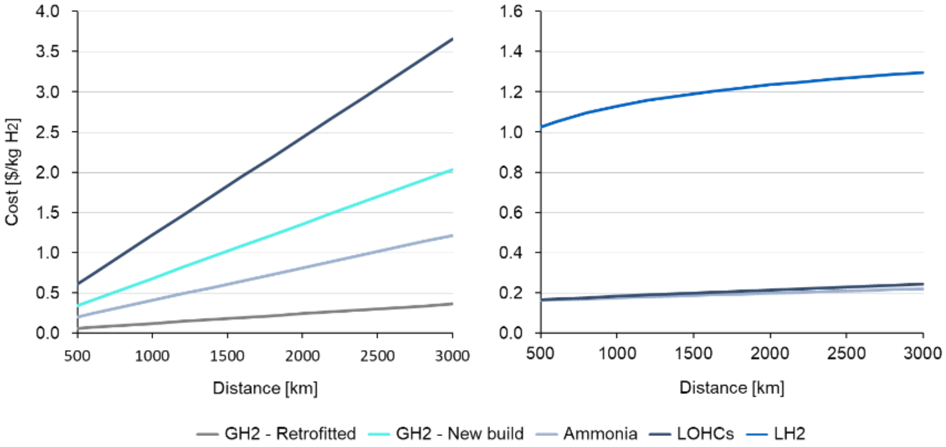


Figure 3-2: Levelised costs for long-distance transportation of hydrogen via pipeline (left) and ship (right)[55,56,57,58].

Based on the figure above, it can be concluded that shipping transportation is more cost effective for the distances considered. However, pipeline costs are dominated by their capital expenditure, suggesting that, for any given transportation distance, the larger the transportation volumes, the lower the $/kg H_2 as a function of distance (see example in Figure 3-3).

Transportation of hydrogen over medium distances

As transportation distance requirements decrease, a wider range of options which can carry lower hydrogen volumes become cost effective, namely trailers, distribution pipelines and trains, although the latter can cover larger distances.

[52] Dagdougui et al. Hydrogen Infrastructure for Energy Applications: Production, Storage, Distribution and Safety (2018).
[53] Sari Energy, Natural Gas Value Chain: Pipeline Transportation
[54] IEA and HIA, Large-Scale Hydrogen Delivery Infrastructure (2015)
[55] Levelised costs for transportation is defined as the present value of the transported hydrogen price, considering the economic life of the transportation method and the costs incurred during the construction, operation, and maintenance.
[56] Navigant, Gas for Climate: Optimal Role for Gas in a Net Zero Emissions Energy System (2019). LOHC molecule and transportation volumes not specified.
[57] Various gas operator authors, European Hydrogen Backbone, (2020). GH_2 pipeline – Retrofitted: Transportation of 5,000 tpd H_2.
[58] IEA, The Future of Hydrogen (2019): Transportation volumes per pipeline: 340 tpd H_2 for GH_2 new build and 240 tpd H_2 for ammonia. Transportation volumes per ship: 11,000 tonnes for LH_2; 110,000 tonnes for LOHCs (toluene) and 53,000 tonnes for ammonia.

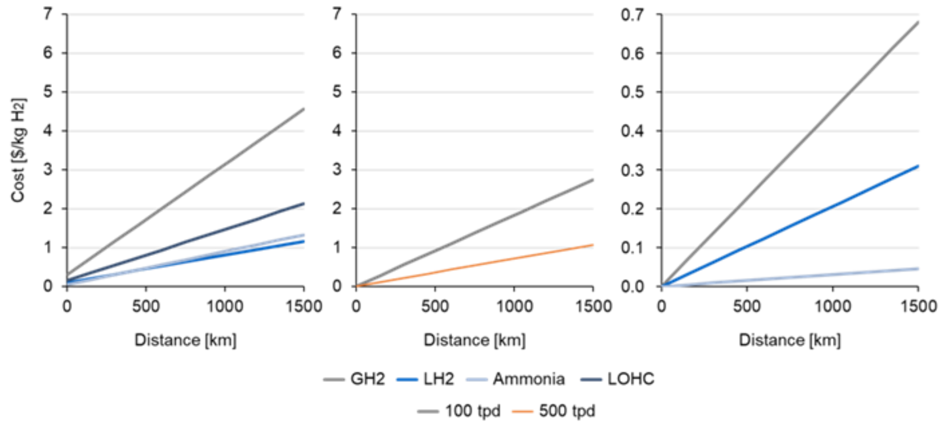


Figure 3-3: Levelised cost for medium-distance transportation of hydrogen via trailer (left), pipeline (centre) and train (right)[59,60].

For the ranges of scale and transportation distances considered in this study, economic performance of transportation by trailer and pipeline is very similar up to 500km, except for transportation of GH_2 by trailer. Nevertheless, the scales of demand which pipelines can achieve are higher than those of trailers (roughly, a 100tpd pipeline can deliver in a day the same hydrogen as 23 LH_2 trailers).

For all the hydrogen archetypes considered, transportation by rail is considerably cheaper than by distribution pipelines and trailer. It is noteworthy to mention that the costs of building new rail infrastructure have not been included in this analysis/research. At a general level, transportation by trailer shows a higher cost sensitivity with distance relative to rail, for all hydrogen archetypes considered.

Daily hydrogen demand is a key driver for transportation costs for last mile distribution

All the examined regions have shown interest in the application of hydrogen in the mobility sector. Figure 3-4 exhibits the costing for the short-distance delivery of hydrogen (10km-50km) to a hydrogen refuelling station (HRS) via new or retrofitted GH_2 pipelines or via trailer carrying LH_2 or GH_2 from a centralised production site[61]. Costs are presented for an HRS servicing heavy road vehicles and the design capacity of the HRS varies from 500 to 5,000 kg H_2/day.

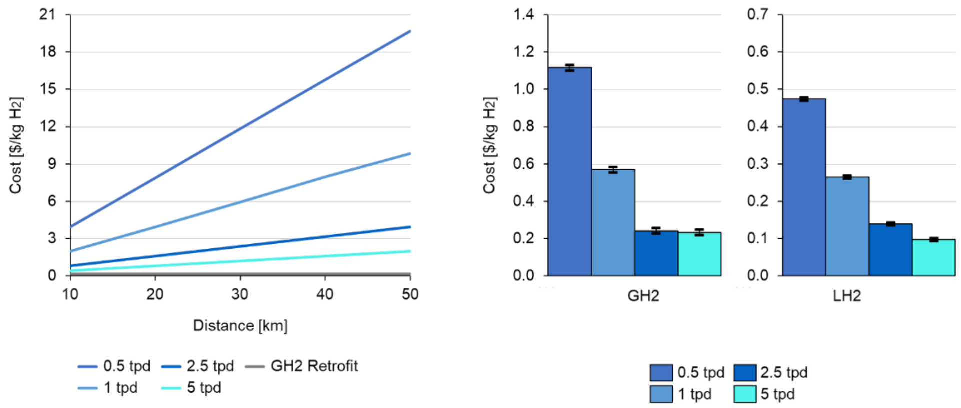


Figure 3-4: Levelised cost for last-mile delivery cost for hydrogen via pipeline (left) or trailer (right).

The bars on the trailer graph indicate the range of levelised costs for the distances considered (10km-50km), suggesting that, for a given tpd delivery, trailer delivery costs remain almost constant in the distance range

[59] IEA, The Future of Hydrogen (2019): Transportation volumes per trailer: 670 kg H_2 for GH_2; 4,300 kg H_2 for LH_2; 1,800 kg H_2 for LOHC and 2,600 kg H_2 for ammonia.

[60] Train costs from Bruce S, Temminghoff M, Hayward J, Schmidt E, Munnings C, Palfreyman D, Hartley P (2018) National Hydrogen Roadmap. CSIRO, Australia. GH_2 (430 bar, 36.2 m^3 H_2), LH_2 (56.2 m^3 H_2) and ammonia (3.8 tonnes H_2).

[61] Element Energy internal modelling. Assumptions: HRS utilisation=90%, trailer lifetime=11 years, trailer capacities=4,000 kg (LH_2) and 1,000 kg (GH_2), diesel HGV tube trailer powertrain. Depending on design capacity, liquefaction costs for LH_2 add anywhere in between \$1/kgH_2 to \$1.3/kgH_2 whereas compression costs for GH_2 add \$0.3/kgH_2.

analysed. This small variation between 10km-50km is due to the higher fuel costs as distance increases. Retrofitting a natural gas pipeline for GH_2 delivery shows almost invariable costs at \$0.13/kgH_2. For all forms of hydrogen delivery, the economics for last-mile delivery of hydrogen improve as the design capacity is increased.

Interseasonal storage of hydrogen

As demand for hydrogen grows, the need for high-scale storage of hydrogen will be necessary. Interseasonal hydrogen storage is a form of energy security and ensures that demand from high-energy consuming sectors, such as the residential sector, can be met throughout the year.

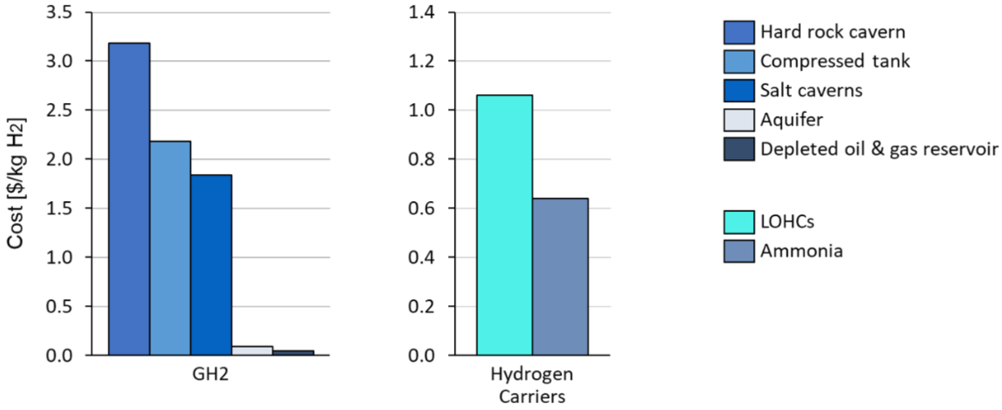


Figure 3-5: Levelised cost for interseasonal hydrogen storage in compressed gas form (left) and as hydrogen carrier (right)[62,63,64,65].

Even though underground storage is only possible based on geographic location, interseasonal storage of hydrogen in underground pipes in the form of GH_2, ammonia or LOHCs can be strategically located close to demand centres as to minimise the transmission costs.

As exhibited in Figure 3-5, for the storage volumes considered, both ammonia and LOHC tanks show the lowest storage costs of interseasonal storage. Nevertheless, these require conversion and reconversion steps, taking the final costs before end use to cost levels similar to those exhibited by GH_2 in salt caverns.

Even though hydrogen storage in aquifers and depleted oil and gas reservoirs show the most favourable economics, it is noteworthy mentioning that using these geological formations could potentially incur additional purification costs to remove impurities after hydrogen withdrawal.

[62] Argonne National Laboratory, System Level Analysis of Hydrogen Storage Options (2019). GH_2 compressed underground pipes: 500 tonnes of H_2 and discharge cycle of 10 days (50 tpd).
[63] Jeffrey Bartels, A Feasibility Study of Implementing an Ammonia Economy (2008). Ammonia pressurised vessel capacity: 15,000 tonnes of ammonia, one full cycle per year.
[64] Reuss et al., Seasonal Storage and Alternative Carriers: A flexible Hydrogen Supply Chain Model (2017).
[65] Sandia National Laboratories, A Life Cycle Cost Analysis Framework for Geologic Storage of Hydrogen (2011). Salt cavern: 6,200 tonnes of H_2 and discharge cycle of 37 days (120 tpd). Depleted oil and gas reservoir: 7,100 tonnes of H_2 and discharge cycle of 60 days (60 tpd). Aquifer: 7,100 tonnes of H_2 and discharge cycle of 60 days (60 tpd). Hard Rock Cavern: 6,200 tonnes of H_2 and discharge cycle of 37 days (120 tpd). Calculations account for cushion gas volumes.

Intraday storage of hydrogen

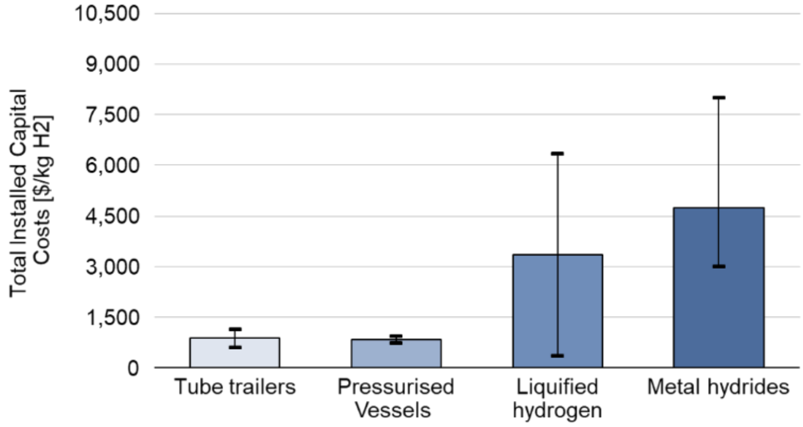


Figure 3-6: Average total capital cost of pressurised vessels normalized to storage capacity, with upper and lower limits[66,67,68].

Costs for the intraday storage of hydrogen have not been reported in levelised form as these are influenced by multiple factors including amount of storage time, discharge and compression rate requirements, electrical energy costs, and others. These factors strongly determine the operational costs of the storage technology. Therefore, a cost comparison is done based on the total installed capital costs, as shown in Figure 3-6[69]. Maximum and minimum values have been included for each option as the economics for intra-day storage vary depending on the design pressure and capacity.

For the range of storage volumes considered, the lowest capital costs are exhibited by GH_2 storage in tube trailers and pressurised vessels. Storage of hydrogen in this form has been used widely in the past decades, and this storage technology has therefore reached technological maturity. In addition to the technological maturity, the lower pressures required for storage makes tube trailers and pressurised vessels less capital intensive than liquefied hydrogen storage or metal hydride storage. The two latter technologies are still to benefit from further technology developments. In the case of LH_2 storage, the capital costs go down considerably as the storage volume capacity increases, as seen in Figure 3-6.

[66] Tube trailers and pressurised vessels calculated using internal Element Energy analysis. Tube trailer capacity volumes: 320 kg H_2 to 1,100 kg H_2. Pressurised vessel capacity volume: 300 kg H_2 to 1,000 kg H_2.
[67] Liquefied storage tanks costs from Tzimas et al., Hydrogen Storage: State-of-the-Art and Future Perspective (2003). Liquefied tank capacity volumes: 1,000 kg H_2 to 150,000 kg H_2.
[68] Metal hydride storage tank costs from i) Ganda et al, Economic Data and Modelling Support for the Two Regional Case Studies: Nuclear-Renewable Hybrid Energy Systems: Analysis of Technical & Economic Issues. Argonne National Lab, 2018 and ii) Nils Bornemann, GKN's Solid-state Hydrogen Storage System, 2017. Metal hydride capacity volume: 160 kg H_2 to 890 kg H_2.
[69] The total installed capital costs normalise the capital costs of a storage technology to the amount of hydrogen it can store i.e. if a storage tank costs $1,000 and can store 10 kg of H_2, then the total installed capital cost is $100 per kg H_2.

4 Regional summaries and recommendations

As presented in this study, there are a wide set of options for the transportation and storage of hydrogen. Based on the findings for the regional suitability of different transportation options, along with the techno-economic analysis for the different transportation and storage options, this study provides a series of recommendations for each region.

4.1 North Rhine-Westphalia

North Rhine-Westphalia's large industrial energy demands coupled with the region's highly populated areas and large transport systems suggest that the region could become a major consumer of hydrogen in the transition to a decarbonised economy. Regional options for storage mean that hydrogen constitutes a viable solution to both replace fossil fuel combustion in power generation and manage interseasonal fluctuations of renewable electricity production. Part of the hydrogen production can be expected to be local; however, the region is expected to also rely to on imports of green hydrogen either from other regions or from overseas.

Lowest cost transportation options can come from natural gas pipeline repurposing

The expected short and long hydrogen transportation distances required for North Rhine-Westphalia along with the potentially high volumes of hydrogen demand from industrial clusters suggest that conversion of natural gas transmission pipelines to GH_2 provide the most cost-effective solution. However, the use of GH_2 pipelines for imports from sources producing blue hydrogen may impact Germany's long-term objective of transitioning to green hydrogen only.

Using the Rhine river for transhipment of hydrogen imports could help the region overcome this issue. At present, long-distance transportation by ship is cheapest in the form of ammonia and LOHCs. However, much of the future hydrogen demand in the region could be for industrial feedstock, implying that high purity hydrogen would be needed. Use of LH_2 ships would provide high purity hydrogen streams, although this option is noticeably more expensive than shipping by ammonia and LOHCs. Medium to long term improvements in the conversion purity of ammonia and LOHCs to hydrogen as well as in the economics of liquefaction could result in similar delivery costs for hydrogen in its final form[70]. If hydrogen is to be imported as ammonia and LOHCs, the overall economics of the supply chain would be more competitive if sufficient infrastructure in the ports is deployed as to allow centralised conversion of these commodities to hydrogen.

Large amounts of hydrogen storage could be required in the long-term

It has been forecasted that between 3-13 TWh of hydrogen storage capacity could be required for North Rhine-Westphalia in 2050[71]. While hydrogen storage in salt caverns could cover a significant amount of the storage needs cost-effectively, their current use for natural gas storage means that this form of underground storage will not be available any time soon. Additionally, development of new dedicated storage sites would take approximately ten years. It is expected that demand, especially from industry, will ramp up before these become available.

In the short to medium term, the most recommended solution for hydrogen intraday storage will therefore depend on volume of demand. For industrial sites close to one another, such as steel sites in the Ruhr region, the sharing of infrastructure to use LH_2 could result in reduced storage costs. For more dispersed applications with reduced storage needs, storage of GH_2 in compressed tanks or tubes, either for interseasonal or intra-day storage, shows better economic performance relative to LH_2 storage. In addition, storage in compressed tanks or tubes would show hydrogen supply chain synergies if these options are combined with transportation of GH_2 by pipelines.

[70] Indicative case study for LH_2, ammonia and LOHC transportation costs from overseas to a regional port in Rhine river (e.g. Duisburg): based on the techno-economic analysis on current costs presented in Chapter 3.2, the conversion, import via ship (distance of 3,000km) and centralised reconversion to GH_2 would result in supply chain costs of: \$2.3/kg H_2 for LH_2, \$2.0/kg H_2 for ammonia and \$1.7/kg H_2 for LOHCs. No production nor storage costs considered.

[71] Ministerium für Wirtschaft, Innovation, Digitalisierung und Energie des Landes Nordrhein-Westfalen, Wasserstoffstudie Nordrhein-Westfalen (2019).

Closer collaboration between the government and its industries would support industrial hydrogen clusters

There is a large potential for a variety of industries (iron and steel, refineries, and chemicals) spread throughout the six regions of the state of North Rhine-Westphalia to become important consumers of hydrogen. The growth of public-private partnerships (PPP) between the regional government and industries is advised to facilitate the timely deployment of infrastructure. These PPP could be formed by stakeholders present in the different stages of the supply chain, hydrogen producers and transportation/ supply chain operators. These PPP would help identify where opportunities for collaboration exist between the different industrial clusters i.e. how producers and consumers of hydrogen would be distributed among these clusters and how these clusters could be better connected via hydrogen transportation links. A structured integration of the supply chain for hydrogen would help de-risk private investments and help exploit the large economies of scale benefits that exist for hydrogen[72].

The regional government can also collaborate with North Rhine-Westphalia industries by supporting the dissemination of learnings which result from the commissioning of first-in-the-region industrial hydrogen projects. Future projects could support the demonstration of hydrogen use in specific industrial processes, and because there are multiple companies operating in the region within each industrial subsector (various refineries, chemical sites etc.), the regional government can act as a platform though which learnings and industrial hydrogen knowledge can be shared with sites where analogous hydrogen projects are possible.

4.2 Zuid-Holland

Zuid-Holland is currently concentrating on the use of hydrogen in the industrial and mobility sectors. The region's large network of natural gas pipelines implies that, although receiving less attention, uptake of hydrogen in the power sector as well as in the residential sector are both viable options. Hydrogen production is expected to be in the POR industrial cluster, where significant hydrogen industrial demand could develop in the future. In the medium to long term, provision of hydrogen in Zuid-Holland is expected to shift from regional production to imports of green hydrogen.

Potential industrial demand heavily influences transportation options

Transportation of hydrogen by rail to meet industrial demands for all hydrogen archetypes offers the lowest cost solution. However, a GH_2 pipeline network is most advisable, the future industrial demand volumes expected. Use of a GH_2 pipeline network is currently being considered by the POR and Zuid-Holland, and it is recommended that the reuse of existing natural gas infrastructure is maximised. A GH_2 pipeline network would bring the lowest cost solutions for hydrogen delivery both for POR and other industrial clusters.

If connections to GH_2 pipeline to meet demands in the mobility sector are not possible, last mile delivery by trailer is advised either in the form of GH_2 or LH_2. Considering that many of Zuid-Holland's roads are logistics corridors, the high potential hydrogen demand makes LH_2 a cost-competitive option. However, the region needs to ensure that sufficiently large hydrogen demand for mobility exists so that LH_2 economies of scale reduce costs throughout its supply chain.

Zuid-Holland has an advantaged access to waterways e.g. the Rhine river which connects the region with North-Rhine Westphalia. As of today, shipping in the form of ammonia and LOHCs are the cheapest options to transport imported hydrogen from overseas[73]. However, by the time sufficient hydrogen demand has been created, it is likely that a GH_2 pipeline network will exist. Conversion to GH_2 in ports or alternatively, train or trailer transportation of ammonia and LOHCs to regional points of use would therefore be advised. However,

[72] Thyssenkrupp's project at their Duisburg site to convert all its blast furnaces to hydrogen in 2022 has noted that if supply of hydrogen is not sufficient, the furnaces will run on natural gas.

[73] Indicative case study for LH_2, ammonia and LOHC transportation costs from overseas to POR and latter transportation via pipeline to hinterland industrial clusters: based on the techno-economic analysis on current costs presented in Chapter 3.2, the conversion, import via ship (distance of 3,000km), centralised reconversion in POR to GH_2 and subsequent GH_2 transportation via new GH_2 pipelines (distance of 500km) would result in supply chain costs of: \$2.7/kg H_2 for LH_2, \$2.3/kg H_2 for ammonia and \$2.0/kg H_2 for LOHCs. No production nor storage costs considered.

road or rail transportation of ammonia and LOHCs is subject to reconversion and purification costs decreasing in the future for both archetypes.

Hydrogen storage in Zuid-Holland could come in many forms

The expected short-term regional production of blue and green hydrogen suggests that intraday storage is most cost effective in pressurised GH_2 vessels. Moreover, demand for storage is currently low, making pressurised vessels a great option for specific stationary storage needs. However, for intraday storage applications where large quantities of hydrogen are needed, such as in industrial sites, LH_2 can outperform pressurised vessels.

In the long-term, once hydrogen demand has considerably grown in industry and transport, salt caverns in the north of the country could become available for interseasonal storage of hydrogen. Nevertheless, if green hydrogen import projects such as the Green Spider project go forward, storage in the form of LOHCs would show better storage economics following the repurposing of oil and gas storage infrastructure in the POR. An interplay of both options could result in optimal interseasonal storage economics, where LOHC storage infrastructure is used to store imports, and salt caverns are used to store nationally produced green H_2 using offshore wind.

Additional policies would support industrial demand pull for hydrogen

Whereas supportive regional policies and funding programmes for projects have been implemented in the production stage of the supply chain, it is important that these are matched with policies to encourage industrial hydrogen demand uptake. While the EU Renewable Energy Directive II can support industrial decarbonisation, Zuid-Holland should ensure that this decarbonisation focuses on the uptake of hydrogen for high temperature applications. Fuel switching regional funding programmes for specific industrial processes, such as the use of hydrogen in boilers in refineries, can be a good starting point to catalyse demand.

4.3 Hauts-de-France

Hauts-de-France's large and varied industries as well as the region's extensive transport network system with its wide range of transportation methods constitute two important sectors in which hydrogen demand could grow. These sectors, which are geographically dispersed across the region, could result in multiple hydrogen demand locations. Decentralised green hydrogen production is thus expected to play an important role, where hydrogen supply chains are short. Nevertheless, hydrogen imports would need longer transportation distances.

Liquefied hydrogen could play an important role in the regional supply chains

The recommended hydrogen transportation method strongly depends on the dominant form of hydrogen production i.e. either centralised or decentralised. If the former dominates, hydrogen production centres should be located in industrial clusters, where demand is expected to grow. In cluster transportation of hydrogen would then be most cost-effective using GH_2. Even though transportation via ammonia pipeline is cheaper, the hydrogen purity requirements by certain industrial sites using hydrogen as feedstock implies that GH_2 is most suited, as purity improvements are needed for the reconversion of ammonia.

Large-scale, centralised production of hydrogen would enable transportation of hydrogen to HRSs and dispersed industrial sites in the form of LH_2 by train or rail, which could be cheaper than transportation as GH_2[74]. However, this would be contingent to the centralised production of hydrogen and the subsequent liquefaction of part of the hydrogen produced, so that economies of scale benefits for liquefaction can be realised. If the region sees a larger push for decentralised production, then transportation requirements may be most cost competitive by GH_2 trailer.

[74] Indicative case study for GH_2, LH_2, ammonia and LOHC transportation costs from Dunkirk industrial cluster to an HRS in Amiens: based on the techno-economic analysis on current costs presented in Chapter 3.2, the conversion, trailer transportation (distance of 160 km), decentralised reconversion in the HRS to GH_2 would result in supply chain costs of: \$0.75/kg H_2 for GH_2, \$1.2/kg H_2 for LH_2, \$2.2/kg H_2 for ammonia and \$2.90/kg H_2 for LOHCs. Nevertheless, realisation of economies of scale for liquefaction as suggested in ref. 34 could bring LH_2 down to \$0.55/kg. No production nor storage costs considered.

In the long-term, as hydrogen demand grows and hydrogen imports are needed, retrofitting GH_2 pipelines to import could be the cheapest option. However, repurposing natural gas pipelines may not be possible as long distances to export hubs (+500km), crossing various countries, could make it difficult for infrastructure repurposing. In such cases, the recommended option largely depends on the transportation distances covered by the imports i.e. pipeline vs shipping, where pipeline transportation would only be advised for less than 500km delivery. Beyond such distances, ship imports as ammonia and LOHCs would become more cost-effective.

Storage as GH_2 in pressurised vessels or tanks exhibit the best suitability

Decentralised production of green hydrogen in HRSs may require intra-day, small scale hydrogen storage to balance production fluctuations to balance intermittency if the production of hydrogen is not performed using the region's carbon-free grid. For these purposes, storage in pressurised vessels would be the most advisable option in terms of economic performance.

Hydrogen storage needs in industry would largely depend on the security of hydrogen supply. Local blue hydrogen production in industrial sites, which would have a constant supply of natural gas given the region's storage sites, would be capable of providing a continuous supply of hydrogen to meet industrial needs. However, if hydrogen production in industrial clusters is mostly green, then hydrogen storage would most likely be required. An existing supply chain of hydrogen in LH_2 form as described above with large liquefaction plants in industrial sites could be used as a form of storage, especially if storage is for short term applications. Longer-term storage of hydrogen in compressed tanks would then be the most cost-effective option, as storage of hydrogen in some of the region's aquifers cannot provide sufficient cyclability to support storage needs for industry.

Demonstration projects for hydrogen in industry would promote hydrogen uptake

Hauts-de-France has recognised the prominent demand for hydrogen which could arise in the transport sector. However, industry could also become an important demand sector for hydrogen. Currently there are few examples of regional projects for the adoption of hydrogen in industry, either for high temperature applications through fuel switching or as feedstock for industrial processes. It is advised that Hauts-de-France supports the implementation of demonstration projects in industry to accelerate uptake. Because the recommendations given above are most suited for a scenario where there is a simultaneous uptake of hydrogen in transport and industry, the realisation of economies of scale benefits for the recommended transportation and storage methods would not be possible if hydrogen growth comes from transport only

4.4 Scotland

Due to its wind and geological resources, Scotland has a vast potential for a surplus production of hydrogen and thus for the export of hydrogen to other markets. Centralised production of hydrogen is most likely to be in coastal areas i.e. in natural gas processing plants and close to offshore wind plants. Uptake of hydrogen in the residential or transport sectors could make demand for hydrogen dispersed around Scotland, whereas demand growth in the industrial sector would be more concentrated in the Central Belt of Scotland.

Most suitable transportation method is heavily influenced by a residential uptake of hydrogen

The most suitable form for the regional transportation of hydrogen would depend on the volumes required. Delivery to industrial sites via repurposing of existing natural gas infrastructure would be the lowest cost option. However, repurposing this infrastructure may only be possible if large volumes of hydrogen are required, as the natural gas throughput of the Scottish pipeline transmission system is very large. For smaller volumes and a relatively constant hydrogen demand e.g. a city such as Edinburgh using hydrogen for heating with a potential to consume around 400 tpd of hydrogen, construction of new GH_2 pipelines would be the cheapest form of transportation.

Transportation of hydrogen for exports to other European markets would need to be carried out via ship. Any form of hydrogen transportation via pipelines, for the distances considered (+500 km), show less favourable economics and their use would require a very secure source of demand. Repurposing existing natural gas pipelines, even if offshore, may not be possible due to the role these constitute for the North Sea natural gas supply chain. Exports via shipping would allow Scotland to enter markets with very high potential for hydrogen use e.g. Zuid-Holland or North-Rhine Westphalia via direct Rhine river access[75]. For any distance considered, shipping hydrogen in the form of LOHCs or ammonia would be most cost competitive and shows high distribution flexibility. However, the reducing marginal cost of shipping LOHCs or ammonia with distance means that export could be done to very distant sources i.e. +3,000km.

Large scale storage of hydrogen may only be required under certain circumstances

Large scale, interseasonal storage of hydrogen would be most likely required either to meet Scottish heating demands following a hydrogen uptake from the residential sector or in ports to meet export levels. The lack of underground storage capacity in salt caverns implies that storage alternatives such as LOHCs and ammonia need to be considered. This is because interseasonal storage as GH_2 in compressed tanks is up to three times more expensive than ammonia storage. Unless the stored hydrogen is used for exports as ammonia or LOHCs, an additional reconversion step is likely to be required prior to domestic use of the hydrogen.

Intra-day storage needs in Scotland may be low if the centralised blue production of hydrogen is combined with transportation via GH_2 pipelines, as hydrogen fluctuations could be met by ramping up or down production as needed. Conversely, a high percentage of green hydrogen production may require storage infrastructure for constant supply. For intra-day storage demands, storage of GH_2 in tube trailers or in pressurised vessels would be the most cost-effective form, especially for uses where storage demands are low, such as remote distilleries or HRSs with low utilisation rates. For higher storage needs, such as storage for industrial purposes, LH_2 shows better economies of scale, especially if it is employed in industrial clusters with high demand.

The potential for exports should be explored with likely importing regions

As highlighted in this section, exports will be a key element for the planning of infrastructure in Scotland, and certainty for demand is needed before making the large investments required to establish export supply chains. Materialising Scotland's potential requires the active engagement with other regions expected to become importers, such as those in northern of Europe. Some of these regions are already evaluating the import of hydrogen from other regions with high potential for the production of green hydrogen, such as imports from Spain as per the Green Spider project[55]. It is advised that Scotland accelerate its cooperation with other regions and perceive the creation of market for hydrogen exports as independent from future evolution of endemic hydrogen demand.

4.5 Alberta

The region's vast oil and gas reservoirs and storage availability for CO_2 along with its solar PV and wind resources constitute a promising opportunity for the region to produce hydrogen from a wide variety of sources. Hydrogen, which is already produced in the order of millions of tonnes a year, can find new uses in the mobility sector for the distribution of heavy goods via transport corridors as well as in the power and heating sectors.

Transportation by trailer is expected to be an important form of transportation

Location of solar PV and wind capacity to produce green hydrogen may be remote and thus require the build-out of transmission infrastructure to connect green hydrogen production with demand sources, which are expected to be at a distance of a few hundred kilometres. If green hydrogen is to be produced in the same location as the solar PV or wind turbine farms, then transportation of hydrogen to demand sources would be most cost-effectively done using trains. Despite transport by rail being cheaper via ammonia or LOHCs, these would require conversion facilities at the point of green hydrogen production, which would the overall supply chain costs.

[75] Indicative case study for LH_2, ammonia or LOHC transportation costs from Scotland (Peterhead) to Dunkirk, POR and Duisburg ports: based on the techno-economic analysis on current costs presented in Chapter 3.2, the conversion, import via ship (approximately 1,000 km to all three ports) and centralised reconversion to GH_2 would result in supply chain costs of: \$2.1/kg H_2 for LH_2, \$1.95/kg H_2 for ammonia and \$1.6/kg H_2 for LOHCs. No production not storage costs considered.

Blue hydrogen production is expected in industrial clusters, where hydrogen demand can potentially grow and where natural gas and CO_2 infrastructure is expected to be available. In these sites, transportation within the industrial cluster would be most cost effective using GH_2 pipelines. For the transportation of hydrogen to HRSs, if natural gas pipeline repurposing is not possible, the cheapest option would be via train or trailer carrying LH_2, which could be liquefied in the industrial cluster prior to transportation to HRSs.

Transportation of hydrogen to remote areas, when decentralised generation is not cost-effective, should be carried out via trailer. For any distance considered, transportation of hydrogen as ammonia or LH_2 would be the cheapest options. Nevertheless, LH_2 is a more viable option as the hydrogen can be used directly.

Transportation of hydrogen for exports via port of Vancouver using pipelines, either ammonia or as GH_2 with subsequent liquefaction in the port would show similar transportation economics[76].

Underground salt cavern storage is available but may not be necessary

Certain Albertan subsectors have already adopted liquefaction technology for the storage of hydrogen as LH_2. The region has a large potential for the underground storage of hydrogen in salt caverns, as salt deposits run north to south of the region. These are located a few hundred km away from potentially large sources of demand, such as industrial clusters and urban areas. Even though salt caverns can store hydrogen cheaply, their use in Alberta may be subject to hydrogen demand in sectors with seasonal demand i.e. the residential sector. Hydrogen storage needs in industrial clusters may be small, as blue hydrogen production could be varied accordingly to meet demands.

The most cost-effective form of hydrogen storage for HRSs would depend on the form of delivery of hydrogen i.e. GH_2 vs LH_2. The latter is advisable if hydrogen is delivered as LH_2 and if the HRSs supply high volumes of hydrogen – for instance to heavy good vehicles, and if these have high utilisation rates – which would reduce the boil-off associated with long storage times.

Careful infrastructure planning is required to avoid competition with renewables for power

Alberta's ambitions to continue being Canada's leading region for the production of hydrogen during the transition to a decarbonised economy necessitates an aggressive set of policies[77]. There is potential for Alberta to catalyse an early market for hydrogen outside the industrial sector by employing its public purchasing power through green public procurement to support projects which adopt the use of hydrogen fuelled vehicles. In addition, Alberta's parallel ambitions to also proceed with a large-scale rollout of renewable energy capacity for the power sector imply that the region should elaborate an infrastructure plan to avoid competition for renewable capacity between the electricity market and electrolysis for hydrogen.

4.6 Commonalities

When it comes to supply of hydrogen, all regions involved in this study recognise the complementarity of blue and green hydrogen, and the more prominent role that blue hydrogen production may have in the near term. In terms of green hydrogen production, the different renewable electricity targets which each region has set out and respective deployment of renewable capacity suggest that competition could exist when it comes to the deployment of capacity dedicated for green hydrogen production.

Regarding hydrogen demand, there is a special recognition across the examined regions for the potential uses for hydrogen in the transport and industrial sectors. In particular, many hydrogen demonstration projects implemented so far have occurred for transport.

[76] Indicative case study for GH_2, ammonia or LOHC transportation costs from Alberta's Industrial Heartland to Port Metro Vancouver for shipping abroad: based on the techno-economic analysis on current costs presented in Chapter 3.2, the pipeline transport (800 km) to the port and subsequent conversion to either LH_2, ammonia or LOHC would result in supply chain costs of: \$1.55/kg H_2 for LH_2, \$1.55/kg H_2 for ammonia and \$0.95/kg H_2 for LOHCs. If instead of pipeline, rail transport were used for the same route to transport either GH_2, ammonia or LOHCs to the port, the costs would stand at \$1.4/kg H_2 for GH_2 (centralised liquefaction in the port to LH_2 for shipping included), \$1.2/kg H_2 for ammonia and \$0.6/kg H_2 for LOHCs. However, train transportation would result in lower daily transportation volumes per train (few tonnes versus 100s of tonnes via pipelines). No production nor storage costs considered.
[77] Petroleum Economist, Canada to Announce Blue Hydrogen Blueprint (2020)

All regions have expressed their interest in the interregional trade of hydrogen, either because they have recognised that their high energy requirements could lead to hydrogen imports being necessary, or conversely, because surplus hydrogen generation is possible due to resource availability. It is important for regions to accelerate collaboration, define viable transportation routes, and establish cross-border business models which bring certainty both in terms of timeframes for hydrogen growth as well as hydrogen quantities to be expected.

Following an investigation on the regions' plans and potential for hydrogen production and demand, this study has identified Alberta and Scotland as two regions with a large potential for hydrogen exports, whereas Hauts-de-France, Zuid-Holland, and North Rhine-Westphalia will most likely become importers of hydrogen. The four European regions show cooperation is possible to establish viable import-export routes via shipping, using both North Sea ports but also inland waterways such as the Rhine river. Similarly, Alberta could leverage some of its oil and gas infrastructure to establish trading partnerships with neighbouring regions such as oil and gas states of the United States.

Another important commonality between the regions is that initiatives for the uptake of hydrogen have come both from the private and public sectors. In particular to transportation, private gas grid operators from different countries have started cross-collaboration to develop the hydrogen pipeline transportation networks of the future e.g. European Hydrogen Backbone[78]. Regional governments need to adopt a similar position towards realising these transportation synergies by expanding the scope of collaboration to also include other private transportation operators, such as shipping, trailer and rail companies.

[78] Various gas operator authors, European Hydrogen Backbone, (2020).

5 Conclusions

This chapter summarises the overarching learnings and findings from this study. In addition, as a commodity whose growth is sensitive to economic, technical, commercial, and political factors, this chapter also examines how each of the target regions' plans for hydrogen have been affected by the COVID-19 crisis. The chapter concludes the study by providing advice on how regional governments' support in the economic recovery from the COVID-19 crisis can be used to leverage hydrogen uptake to help direct economies towards promoting a green transition.

What are the important factors to consider when regions evaluate different hydrogen transportation and storage options?

The analysis on the hydrogen potential in different regions has been facilitated by assessing possible hydrogen supply and demand options, the distances between them and how these could convert into possible key routes. A high-level techno-economic study was also performed to enable the comparison of the different options for the transportation and storage of hydrogen. Outputs from the regional analysis and techno-economic assessment were then combined to provide recommendations for the transportation and storage of hydrogen in the different target regions.

These findings, albeit coming from the analysis of individual regions, are applicable to regions aiming to understand how the different transportation and storage options can be used to connect potential sources of hydrogen supply and demand:

- Establishing hydrogen value chains at the regional scale requires the parallel analysis of the different transportation and storage options, especially as distance between supply and demand points grows. This is because some transportation and storage options are highly complementary, and their combined usage brings additional value to hydrogen supply chains. For instance, salt cavern storage of hydrogen requires a form of transportation capable of realising the benefits of energy security and low-cost that this form of storage offers e.g. by combining this form of storage with compressed GH_2 pipeline transport or with large-volume shipping options (either as ammonia, LOHCs or LH_2). Conscious of the existing uncertainty around the future evolution of hydrogen demand and supply, the analysis for transportation and storage options should at least consider how infrastructure may become available with time e.g. what the lead times for the preparation of salt caverns for hydrogen storage could be or when any natural gas pipelines routes may become obsolete.
- When evaluating the suitability of different transportation options, it is important to also understand the different end uses for hydrogen i.e. which demand sectors may be the most prominent users for a certain supply chain. This is because different users would need hydrogen in different volumes, purity, and regularity of delivery and this important factor is not always reflected in the economics for the different transportation options. For instance, HRSs have high purity requirements and require delivery volumes for which trailers are highly suited, whereas power stations would have lower purity requirements but higher volume and regularity of delivery to be able to meet fluctuations in demand, in which case pipelines would be most suitable.
- Many forms of energy consumption can be replaced by hydrogen, such as fuel cells replacing internal combustion engines or hydrogen fuelled boilers replacing fossil fuelled equivalents; this is expected to become clearer as the costs for hydrogen supply chains reduce over time. As such, it is important to consider how the existing energy supply chains could potentially accommodate the growth of hydrogen. This requires analysing the potential which a region has to repurpose any existing infrastructure to serve the transportation and storage of hydrogen. This potential for infrastructure repurposing will be largest in those regions which are highly industrialised, which have an array of transportation system options for the interregional transport of goods (including ports), and which have prominent oil and gas infrastructure networks.
- It is important to consider how the transportation and supply options could integrate as they grow. Although the development of hydrogen supply chains so far has been highly localised and route-

specific, larger uptake of hydrogen will result in supply chains merging with time. When planning for investments in hydrogen transportation infrastructure, it is therefore important to evaluate how each mode of transportation will be affected. For instance, a major repurposing of natural gas pipelines could reduce the needs for transportation volumes by trailer or train.

Effects of COVID-19 on hydrogen projects and recommendations for a green recovery

The current COVID-19 crisis is having substantial economic repercussions across the globe and the final extent of the impact across the different sectors of the economy is still to be fully understood. It is important for the energy sector to understand how funds from economic stimulus packages can be used to maintain the momentum for decarbonisation. When developing economic programmes for recovery, there are opportunities for hydrogen to form part of the recovery debate[79].

For the regions considered in this report, the general trend suggests that most hydrogen projects are proceeding as planned. However, when it comes to short-term impact on industrial hydrogen projects, there have been mixed reactions to the crisis, with certain hydrogen projects being delayed. At the regional level, the COVID-19 crisis has not resulted in delays in emission reduction targets nor long-term climate change commitments and, consequently, the existing potential for the creation of hydrogen economies in the future remains unaltered.

Regional governments can coordinate with national governments to include dedicated funds for hydrogen projects in their economic recovery packages. These recovery packages may present the very first opportunity for some regions to take the first steps towards the uptake of hydrogen at scale and budgeting an allocation for hydrogen projects would accelerate this growth. Recovery packages, which can be implemented in the short-term, can focus on deploying mature hydrogen technologies and thus create a demand-pull effect.

COVID-19 has negatively influenced the economics of many projects across the energy industry. It is important that the crisis' impact on the economics of hydrogen projects - many of which were facilitated by regional financial support and with the intention to demonstrate operational viability – is minimised. Removing the added risks generated by COVID-19 can be achieved by providing financial support to cover a portion of the projects' operational expenditure, using policies such as lower electricity taxes for green hydrogen production or through financial mechanisms such as contracts for difference.

It is important for regional governments to consider how recovery funds for hydrogen projects can be aligned with and promote just transition mechanisms, as these are being considered by many regional governments. When allocating future funds, alignment is possible if the considered hydrogen projects exhibit a high potential to both reuse existing knowledge and skills, as well as to reinvigorate certain industries more sensitive to the transition to decarbonised economies. Additionally, regional low-carbon hydrogen projects can prevent carbon leakage and therefore help to retain industrial jobs.

As discussed throughout the report, hydrogen supply chains can cross multiple borders to connect supply with demand. Through collaboration with neighbouring regions or countries, regional governments can merge hydrogen recovery funds and jointly support projects which can achieve larger scale initiatives. Creation of hydrogen supply chains which interconnect different regions, and which attract new investment from private companies, would therefore lead to economic benefits being shared by more than one region.

It is essential to acknowledge that clean hydrogen can address long-term economic growth and be aligned with climate neutrality goals. It is important to push forward with investigations into alternative hydrogen carrier options (such as LH_2, ammonia, and LOHCs) which continue to require investment. Doing so will ensure that these alternatives progress through the innovation chain and that techno-economic improvements are achieved. This will ensure that different hydrogen archetypes in future hydrogen economies can be combined in an optimal way and that there is a sufficiently large pool of cost-competitive options to promote healthy competition in a green recovery.

[79] As a valuable example, the Next Generation EU recovery package is a recovery instrument proposed by the European Commission, which alongside the European Green Deal will be the recovery strategies for the European energy sector. Among the many technology investments which will come through these packages, these strategies will jointly aim to kickstart a clean hydrogen economy in Europe.