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Net Zero Technology Centre
Technology Driving Transition

# Enabling Green Hydrogen Exports

## Matching Scottish Production to German Demand

**North Sea Hydrogen Alliance**

This report prepared and collated by the Net Zero Technology Centre and cruh21 GmBH. Funding was provided by Scottish Government.

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# Executive Summary

This report outlines the opportunities and steps required to unlock the full potential of a green hydrogen collaboration between Scotland and Germany. The aim is to synchronize anticipated green hydrogen production from Scottish hubs with demand centres in Germany, encompassing the entire value chain from production to export and demand fulfilment in both countries. Two critical developmental stages are delineated: Stage 1 (up to 2030), preceding hydrogen pipeline installations, and Stage 2 (2030-2045), involving pipeline commissioning and ramp-up. Emphasis is placed on the importance of strategic planning, investment, and partnerships to realize a sustainable energy future.

This analysis of hydrogen production capability in Scotland is based on the review of existing and planned hydrogen production projects as well as supporting strategies and targets. The evaluation of German demand is based on a metanalysis of existing studies and a review of ongoing projects and announcements. The assessment of the supply chain is the result of a literature review, expert interviews, and compilation of infrastructure development plans and initiatives in Scotland and Germany.

Hydrogen production capability in Scotland is growing, with installed capacity expected to increase at a fast pace from 2025 onwards, eventually surpassing national demand. There is a growing interest in the potential for international trade and the delivery of a secure and efficient European hydrogen supply system, accelerating market development and delivering significant economic benefit.

Consensus among studies indicates uniform hydrogen demand in Germany for 2030, with a wide range of projections for 2045, reflecting differing assumptions about the hydrogen economy and infrastructure development. Nevertheless, it is evident that Germany could assimilate the full capacity of Scotland’s green hydrogen supply.

In the short-term, ammonia emerges as a feasible option for accelerating supply chain development, offering cost-effectiveness and well-planned infrastructure. Technological advancements are anticipated to support comprehensive hydrogen supply chains by 2045, including the establishment of offshore pipelines and enhancements in ammonia utilization, $LH_2$ import terminals and LOHC infrastructure.

The scenarios explored to illustrate development options comprise: Scenario A - Maritime Hydrogen Export to Pipeline Transition, and Scenario B - Hydrogen Pipeline Scale-up. Ammonia emerges as a suitable option for accelerating supply chains prior to 2030, with the long-term scale up to 2045 differing in the set-up and integration of $GH_2$, $LH_2$, and LOHC infrastructure.

Drawing on these scenarios, key fields of action are identified to address challenges and capitalize on opportunities in the development of a hydrogen supply chain between Scotland and Germany. These include conducting comprehensive research, prioritizing investment in technology innovation and infrastructure development, strengthening energy partnerships, monitoring market dynamics, reassessing export targets to align with evolving demand trends and creating subsidies to support early export projects.

The recommendations provided aim to foster a vibrant and interconnected green hydrogen economy between Scotland and Germany. Additional ongoing projects, such as the Hydrogen Backbone Link Project 2 and Project MOHN will further analyse pipeline installation options and distribution network development, respectively.

# Introduction

In recent years the level of engagement between Scotland and Germany on the topic of energy has increased significantly, particularly in regard to the trade of Green Hydrogen. Whilst the potential of Scotland is now well comprehended alongside the predicted demand in Germany, there is a lack of tangible understanding on the alignment of Supply and Demand and its evolution from present day to 2045, when both countries aim to achieve Net Zero carbon emission targets.

This report aims to tie together essential work being undertaken at the Net Zero Technology Centre (NZTC), cruh21 and latest representative studies to provide a holistic overview of the crucial development stages in enabling green hydrogen export and consumption between Scotland and Germany.

A comprehensive bilateral report was developed, assessing the feasibility of exporting green hydrogen production from Scottish hydrogen hubs to large demand centres in Germany. The analysis includes Scottish export / German import scenarios looking at different possible pathways and exploring the needed infrastructure and regulatory frameworks required to enable a safe and effective distribution of hydrogen between Scotland and European demand centres.

The entire value chain is encompassed in this assessment, with emphasis on production, onshore transport, and export terminals in Scotland, offshore transport between the two nations, as well as import terminals, onshore transport, and demand in Germany. Consideration is given to pathways for the trade of hydrogen and its derivatives.

Two key development stages are considered to create a picture of production and end-use based on the respective decarbonisation and export strategies of both countries:

Stage 1 (up to 2030): Encompassing early production and end-use activities preceding the installation of hydrogen pipelines.
Stage 2 (2030-2045): Involving the commissioning and ramp-up of pipeline infrastructure to facilitate enhanced distribution at a low cost.

This report provides an overview of each supply chain step, outlining hydrogen production and distribution options in Scotland, hydrogen demand and transport in Germany, an assessment of supply chain capability and matching scenarios between Scottish supply and German demand.

# Supply chain overview

Over the past years, extensive research has been conducted to develop knowledge and understanding on how the handling, transport and conversion of hydrogen can be processed. This chapter offers a comprehensive overview of various hydrogen carriers, exploring their distinctive characteristics, advantages, and disadvantages throughout the supply chain.

Figure 1 illustrates the different stages of the supply chain, encompassing production, conversion, and onshore transport in Scotland, offshore transport from Scotland to Germany and onshore transport in Germany for gaseous hydrogen (GH$_2$), liquid hydrogen (LH$_2$), ammonia (NH$_3$), synthetic natural gas (SNG), and liquid organic hydrogen carriers (LOHCs).

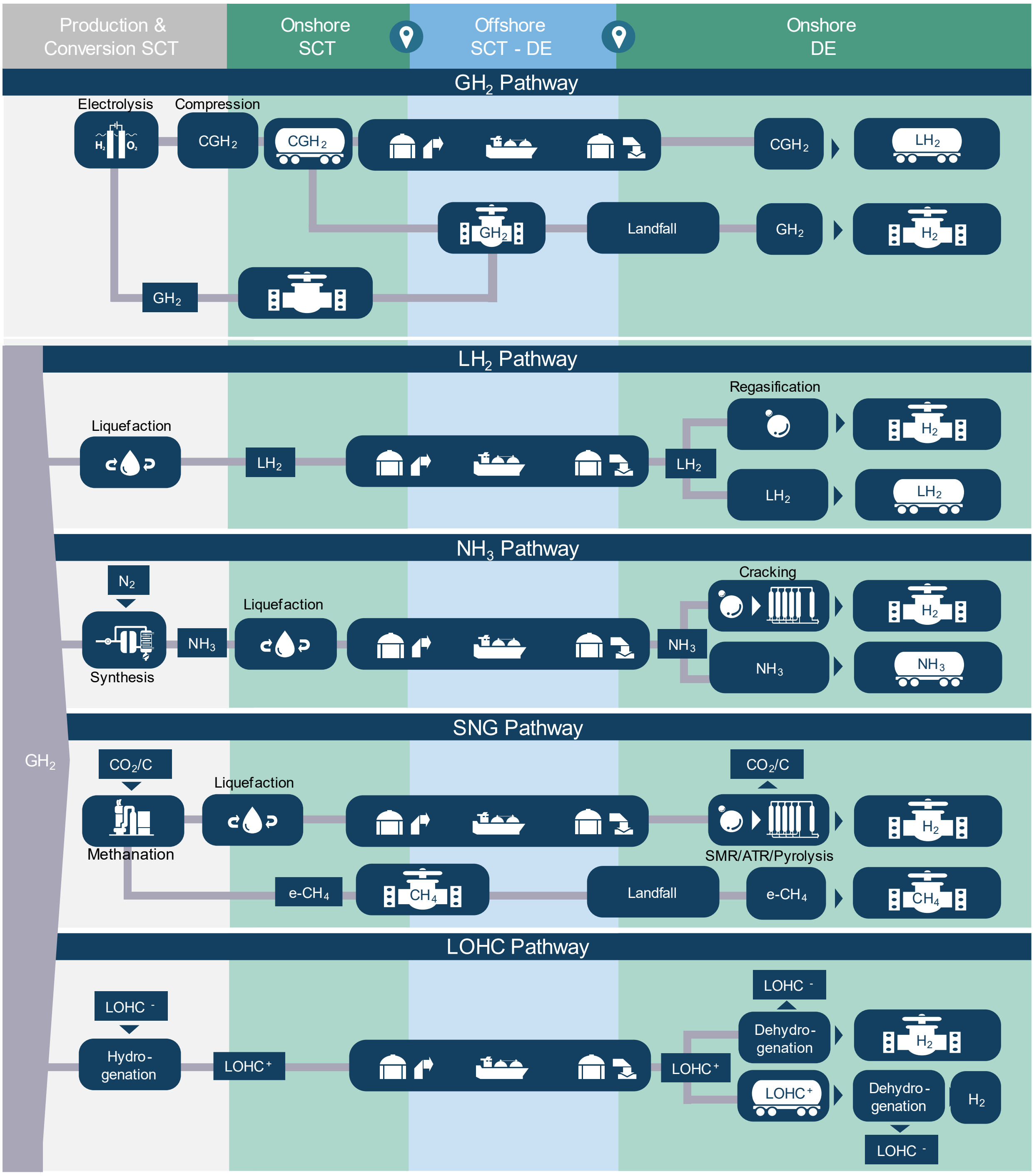

Figure 1: Overview of supply chain steps for hydrogen and derivatives

Each hydrogen carrier has a unique set of advantages and challenges, influencing its suitability for different applications within the hydrogen supply chain. Factors such as energy density, safety, infrastructure requirements, and environmental impact must be carefully considered when choosing the most appropriate hydrogen carrier for a particular use case. Figure 2 summarises the characteristics of hydrogen and its derivatives. [43]

**Gaseous Hydrogen ($GH_2$)**

Energy density: 1.33 kWh/l at 700 bar
Temperature: -245 to 30°C
Pressure: 200 – 700 bar

$CO_2$ source: No
Feedstock: Yes
Fuel: Yes

+
- Decentralised feed-in possible
- No conversion losses
- Infrastructure is already designed for gaseous state
- Blending into the natural gas grid possible
- Cavern storage facilities can be reused
- Non-toxic

-
- Lowest $H_2$ density among carriers
- High energy requirement for compression No mobile storage
- Import via pipeline and therefore path-dependent
- Transport under high pressure
- No diversification of suppliers
- Highly flammable

**Liquid Hydrogen ($LH_2$)**

Energy density: 2.36 kWh/l
Temperature: -252.9 °C
Pressure: 4 bar

$CO_2$ source: No
Feedstock: No
Fuel: Yes

+
- Highest energy density by mass (142MJ/kg)
- High purity
- No need for conversion/reconversion in other chemicals
- Energy consumption required for the transformation of hydrogen into a gaseous state is low
- Possibility to partially recover the cryogenic power of the gasification process
- Non-hazardous to water

-
- Energy-intensive process
- Pre-cooling and liquefaction process requires a significant amount of energy
- Transporting $LH_2$ overseas presents a major technology challenge due to its temperature of -253°C
- While transport is possible via $LH_2$ vessels, this method is still in the pre-commercial phase and has limited capacity
- Subject to boil-off loss during storage and transportation

**Ammonia ($NH_3$)**

Energy density: 3.54 kWh/l
Temperature: -33°C at 1.013 bar or ambient temperature at 9 bar

$CO_2$ source: No
Feedstock: Yes
Fuel: Yes

+
- High hydrogen density (18.6 MJ/kg)
- Existing infrastructure for large-scale transportation and concrete plans to expand capacity
- Direct use as a feedstock to decarbonise fertilisers and chemicals possible
- Competitive costs in case of direct use
- No $CO_2$ required

-
- Toxic and flammable
- Requires special handling and safety precautions (extensive experience in the industry to this regard)
- High energy needed for cracking back into $H_2$
- Low energy density
- Nitrogen necessary
- N2O, NOx emissions

**Synthetic natural gas (SNG)**

Energy density: 6.29 kWh/l
Temperature: -161°C
Pressure: 1.013 bar

$CO_2$ source: Yes
Feedstock: Yes
Fuel: Yes

+
- Part of current energy supply
- Existing infrastructure can be used (ships, terminals, pipelines, etc.)
- High energy density
- $H_2$ gas is obtained from methane via different ways: SMR, ATR, and Pyrolysis
- Non-hazardous to water

-
- $CO_2$ cycle and infrastructure required
- Poor efficiency during production
- Long-term availability/infrastructure
- Methane slip and corresponding climate impact

**Liquid organic hydrogen carrier (LOHC)**

Energy density: 1.90 kWh/l
Temperature: 20°C
Pressure: 1.013 bar

$CO_2$ source: No
Feedstock: No
Fuel: No

+
- Long-term storage
- Easy handling and storage
- Using existing oil infrastructure (ships, terminals, pipelines, etc.) possible
- Easy domestic transport beyond the receiving terminal
- Not highly flammable / volatile
- Reconversion energy needs can be reduced with heat supply

-
- High energy requirement in the process chain
- No direct utilisation
- Innovation and testing needed to further improve efficiency
- Low storage density
- Large quantities of carrier medium required
- Some LOHC carriers can be toxic and/or health-hazardous (water hazard class 3)

Figure 2: Characteristics, advantages and challenges of hydrogen and its derivatives.

Transporting hydrogen and its derivatives involves energy losses along the supply chain. Table 1 shows the supply chain efficiencies determined in six studies. The differences between the studies result from their assumptions on the efficiency of each supply chain step.

The liquid hydrogen supply chain has the highest efficiency, followed by ammonia and LOHC. SNG has the lowest efficiency, highlighting that it is considered without reconversion to hydrogen. In this case, steam reforming (efficiency: 60-70%) with carbon capture, pyrolysis or autothermal reforming would be required, further reducing the overall efficiency. Using ammonia as a feedstock would make ammonia as efficient as liquid hydrogen, as no cracking is required. [110]

Table 1: Various studies on supply chain efficiency in per cent after 2030. [110]

| | JRC | IRENA | Acatech | Hank et. Al | DVGW-ebi | IEA [68] | Range |
|---|---|---|---|---|---|---|---|
| **$LH_2$** | 81 | 71 – 75 | 75 | 67 – 74 | 74 | 73 – 79 | 67 – 81 |
| **$NH_3$ without cracking** | 84 | 76 | 80 | 61 – 67 | 76 | n/a | 61 – 84 |
| **$NH_3$ with cracking** | 56 | 52 – 56 | 75 | n/a | 62 | 63 – 64 | 52 – 75 |
| **SNG without SMR/ Pyrolysis/ ATR** | n/a | n/a | n/a | 56 – 63 | 56 | n/a | 56 – 63 |
| **LOHC** | 47 | 55 – 63 | 68 | 55 – 63 | 68 | 57 – 59 | 47 – 68 |

By examining the properties and operational considerations associated with gaseous hydrogen ($GH_2$), liquid hydrogen ($LH_2$), ammonia ($NH_3$), synthetic natural gas (SNG), and liquid organic hydrogen carriers (LOHCs), insights into the complexities of deploying hydrogen technologies across diverse sectors are gained. Understanding the nuances of each hydrogen carrier is crucial for informed decision-making and the effective set-up of a supply chain between Scotland and Germany. Throughout this analysis hydrogen and its derivatives are considered across the different stages of the supply chain, encompassing production, conversion, and onshore transport in Scotland, offshore transport from Scotland to Germany and onshore transport in Germany.

Expanding beyond the pathways considered in this study, there exists potential for alternative derivatives. Methanol, utilised extensively in the chemical industry and demonstrating promise as a transportation fuel, offers versatility in various applications. Similarly, eKerosene, although still in its infancy, presents a viable solution for decarbonising aviation and research is underway to scale up production facilities. Additionally, Fischer-Tropsch-Crude, although limited in commercial-scale facilities, holds promise for renewable fuel production. Leveraging existing infrastructure for distribution in Germany, e-fuels can be transported via pipelines or tankers. However, the production of all three e-fuels mandates access to $CO_2$ and hydrogen, presenting logistical and environmental challenges, notably in securing sustainable sources of $CO_2$ in Scotland. These hurdles underscore the complexities inherent in transitioning towards renewable and decarbonised fuel sources, necessitating the consideration of specificities on a use-case basis. Accordingly these carriers are not considered in this analysis.

# Hydrogen Supply from Scotland

Scotland's extensive wind resource creates significant potential for electrification and electrolyser-based hydrogen production at a large scale, supporting decarbonisation efforts nationally and enabling the provision of surplus $H_2$ to fulfil demand in continental Europe. The establishment of a hydrogen economy with sizeable export potential can place Scotland at the heart of Europe's near and long-term decarbonisation strategy.

Demand for green hydrogen is growing, particularly in Northern European markets, with Germany currently presenting the largest share of demand in Europe. As routes to market develop, competition for hydrogen supply is expected from countries with abundant renewable resources and low-cost electricity, such as Norway, Southern European and North African countries. The timely and coordinated development of hydrogen transport and distribution systems will be essential to maximise Scotland's export potential.

This chapter provides an assessment of hydrogen production capability in Scotland, including an overview of relevant regulation, the expected ramp up of production volumes to 2045, as well as options for hydrogen distribution nationally and across borders.

## 1. Overview of regulatory framework in Scotland

The potential of hydrogen to decarbonise energy-intensive sectors and drive progress towards net-zero targets is being considered in the development of energy policies and national strategies across the globe. The EU Hydrogen Strategy recognizes the sector's key role in supporting decarbonisation efforts and several member states have announced ambitious government-funded investments in hydrogen.

The Scottish and the UK Governments are committed to the development of a decarbonised energy system and considering approaches that support the reliable and affordable supply and use of hydrogen from the late 2020s onward. The most recent publications in hydrogen policy supporting Scotland's 2045 net-zero target and green energy export ambition are listed in Table 2 below.

Table 2: Political framework in Scotland and the UK.

| Scotland | |
|---|---|
| Hydrogen Sector Export Plan | expected in 2024 |
| Draft Energy Strategy and Just Transition Plan | January 2023 |
| Hydrogen Action Plan | December 2022 |
| Hydrogen Policy Statement | December 2020 |
| Scottish Hydrogen Assessment | December 2020 |

| UK | |
|---|---|
| Hydrogen Production Delivery Roadmap | December 2023 |
| Hydrogen Transport and Storage Networks Pathway | December 2023 |
| Powering up Britain | March 2023 |
| Net Zero Strategy | April 2022 |
| UK Hydrogen Strategy | August 2021 |

The Scottish Hydrogen Policy Statement supports the development of a hydrogen economy in Scotland, setting out a target of 5 GW renewable and low-carbon hydrogen production by 2030 and 25 GW by 2045. This statement also outlines funding mechanisms aimed at supporting the demonstration, development and deployment of hydrogen to drive innovation and technological development at pace. International collaboration and the transition of supply chains, skills and manufacturing capabilities are highlighted as key drivers to the development of a hydrogen economy with global export potential. In support of international export options, the existing natural gas regulatory framework would require minimal modifications to be suitable for the regulation of hydrogen transport.

In addition to the development of a domestic hydrogen economy, there is growing interest in the potential for international trade and the role of collaboration on the development of hydrogen markets. The Scottish Government's Hydrogen Action Plan sets out the ambition to become a net exporter of green energy by 2045, outlining an approach for the development of the hydrogen opportunity in Scotland. Actions are focused on developing capabilities in line with the production targets set out, on the development of Regional Hubs and supply chains to couple production with end-use applications. The aim is to maximise the economic benefits from Scotland's export potential, initiating delivery of hydrogen to centres of demand in mainland Europe by the late 2020s.

According to the Scottish Hydrogen Assessment's Green Export Scenario, 3.3 Mt (126 TWh) of renewable hydrogen could be produced in Scotland by 2045 with around 2.5 Mt (94 TWh) being exported to international markets annually, requiring the deployment of 37 GW of dedicated renewable capacity, predominantly offshore wind. Key figures are shown in Table 3. This scenario maximises Gross value added (GVA) contribution, generating about £26 bn of value by 2045, whilst creating or retaining over 300,000 jobs in the energy sector. Government support through investments in skills, supply chain development and market stimulation can significantly impact the pace of establishment of a hydrogen economy.

Table 3: Key Figures for Green Export Scenario. [105]

| | **Production** | **Use** | | | |
|---|---|---|---|---|---|
| | *Electrolysis* | *Transport* | *Heating* | *Industry & Electricity* | *Export* |
| **Green Export** | 126 TWh | 22 TWh | -- | 11 TWh | 94 TWh |

In September 2023, UK Government signed a Joint Declaration of Intent with Germany to collaborate on the international trade of hydrogen and its derivatives. Due to a natural abundance in wind resources, Scotland is particularly well placed to become a leading producer and exporter of renewable hydrogen and hydrogen derivatives. The existing energy infrastructure, expertise in offshore energy engineering and supportive regulatory environment are key supporting factors furthering the development of the Scottish hydrogen sector.

## 2. Analysis of Scottish hydrogen production until 2045

The European Hydrogen Observatory scenarios for future hydrogen demand anticipate that demand for hydrogen in Europe could reach 220 – 770 TWh/year by 2030, growing to up to 3100 TWh/year by 2050. This growing demand generates a massive opportunity for countries investing in the deployment of hydrogen production systems. Within the UK, it is expected that green hydrogen production could be scaled up to 50 – 180 TWh by 2050, [25] with an anticipated production potential of 126 TWh expected in Scotland by 2045, according to the Scottish Hydrogen Assessment. [105] An alignment of early hydrogen production with market demand is imperative to secure opportunities in the supply of emerging international markets.

Among the existing hydrogen production methods, electrolysis powered by offshore wind is a particularly attractive option in Scotland due to the extensive offshore wind resource and infrastructure available, which can be harnessed for secure and affordable production of green hydrogen. Wind power has taken up a significant share of the electricity network in Scotland already, with electricity generated from wind power (27.8 TWh) exceeding national electricity consumption (27.3 TWh) in 2022. [31] There are currently over 45 GW of offshore wind planned for delivery before 2035 in Scotland (25 GW of it being floating wind), with green hydrogen sites expected to cluster near these wind development areas (Figure **3**). In the longer term, particularly in regions where access to the electricity grid is constrained, green hydrogen production provides an alternative to connection to the transmission system, supporting the commercial development of Scotland's offshore wind resources and avoiding stranded assets.

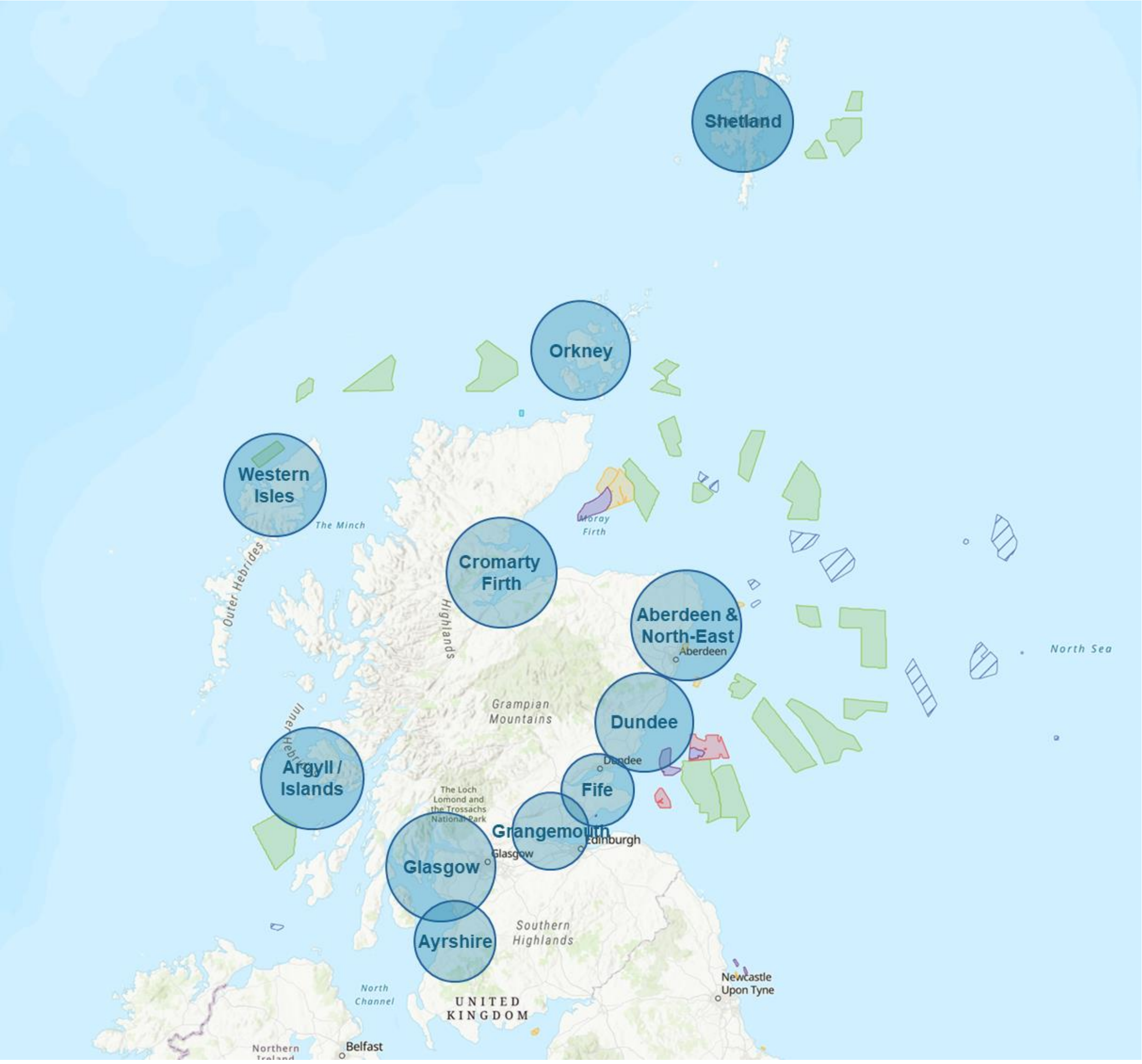

Figure 3: Regional Hydrogen Hubs [106] and Offshore Wind Farm Sites [26] in Scotland.

## Production projects database

Currently, most hydrogen in the UK is produced through steam methane reforming (SMR) or autothermal reforming. In Scotland there is about 4 MW of installed capacity, most of it based in the North East and used locally with distribution undertaken by fuel tankers. In the future, it is expected that production by SMR with CCS or by electrolysis will become the norm. Although the relative cost of electrolysis is still high, falling costs for renewable electricity and electrolyser technology are expected to drive the cost-competitiveness of green hydrogen significantly over the next decade, leading to an expected LCOH reduction of about 75% by 2030. [87]

Scotland is a leading nation in electrolytic hydrogen production with several demonstration-scale projects already operational in coastal areas, where access to offshore wind developments and water is unrestricted and proximity to export points such as ports, terminals and pipeline infrastructure simplifies export to end use points. The development of infrastructure for hydrogen distribution will be essential to a timely development of a hydrogen economy in Scotland.

In order to assess the development of green hydrogen production capability in Scotland, a database of existing and planned production projects was developed. This database includes 64 electrolytic projects at varying stages of development, where planned production data is publicly available[1]. The number of production projects in Scotland is expected to grow steadily in the second half of this decade.

Of the 64 projects identified, about two thirds have concrete plans regarding the production capacity to be installed while nearly one third (19) have not yet defined an expected output for the hydrogen plants to be installed due to being in the early stages of planning. Even so, it is evident that installed capacity will increase at a steady pace between now and 2030, progressing from MW- to GW-scale. As shown in Figure 4, the planned capacity reported exceeds the production targets set out by Scottish Government for 2030, as well as the speed of production ramp-up outlined in the Green Export Scenario. Projections indicate an expected production capacity of 5.7 GW (nearly 20 TWh[2]) by 2030, equating to approximately 30 - 45% of expected demand in Germany.

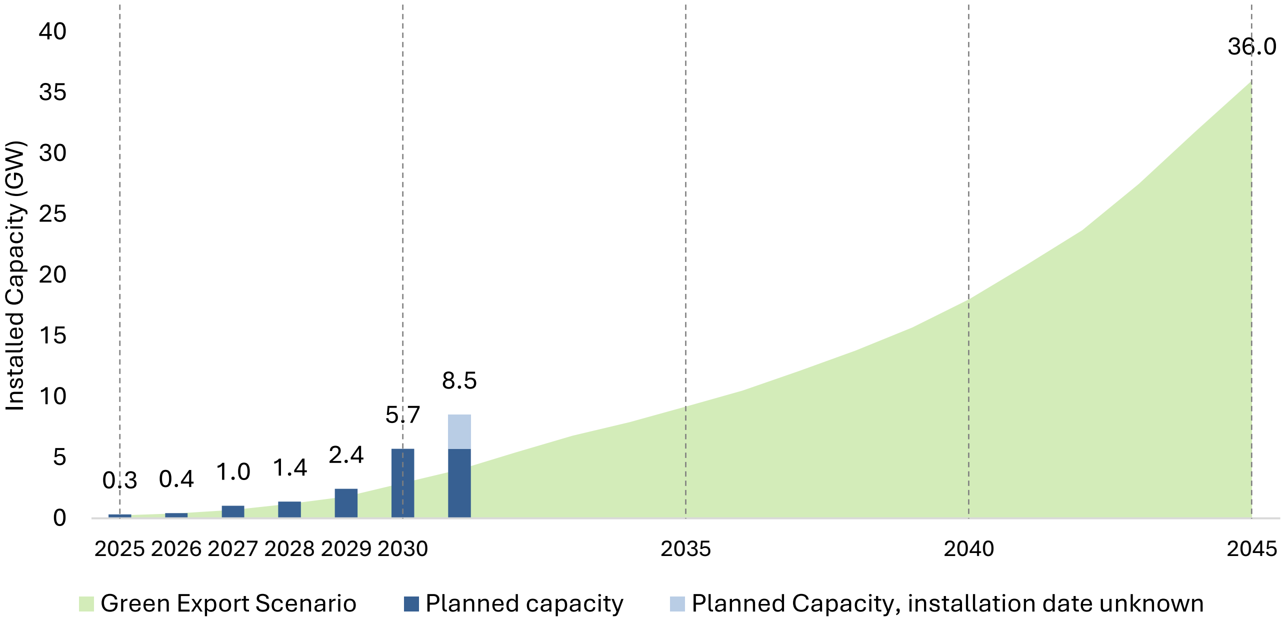

Figure 4: Planned capacity ramp-up from Scottish Hydrogen Production Projects (blue) compared to Green Export Scenario ambition (green).

The vast majority of production capacity is planned in the North East (71%) and Northern Isles (25%) regions (see Figure 5). These locations are already leading the way in hydrogen production and can be

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[1] Announced projects with confidential data were not included in this analysis.

[2] Assuming 69% electrolyser efficiency.

expected to develop into key hydrogen production hubs in Scotland. An abundance of nearby offshore wind sites paired with the availability of coastal infrastructure and industrial development areas locally justifies the fast establishment of production capacity in these regions and makes a case for the planning and development of distribution and export infrastructure locally, supporting the creation of offtake options for these projects and attracting additional investment into these regions.

Operational green hydrogen production projects in Scotland currently total just over 3 GW of installed capacity, a value which is expected to increase quickly. Most planned projects (62%) aim to produce and export hydrogen in gaseous form, but a considerable number of developers have not yet committed to a set distribution vector (see Figure 6).

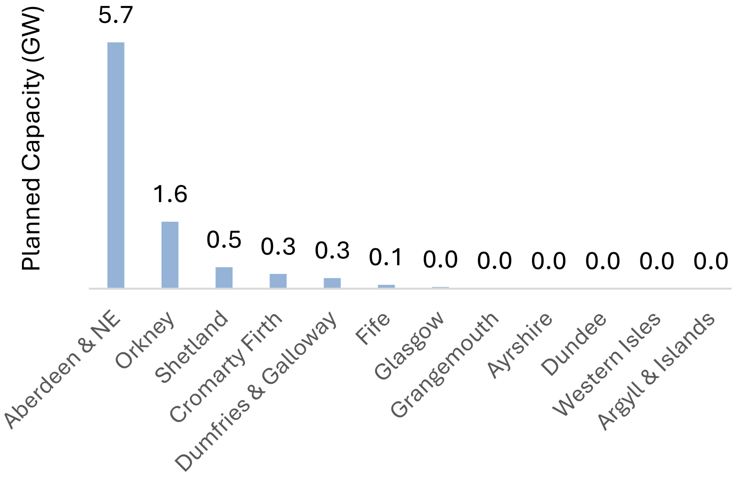

Figure 5: Planned production capacity by region

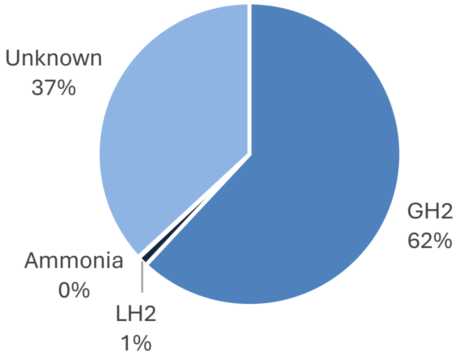

Figure 6: Planned distribution vector

A significant proportion (33%) of planned projects are in the early stages of development, which is expected in the context of an emerging sector (see Figure 7). These early projects frequently report uncertainty around the timeframes for first hydrogen production, expected production volumes and choice of export vectors. A small number of projects have indicated a low commitment to $H_2$ production at this stage, with challenges around project funding and uncertainty on offtake options mentioned by developers as obstacles to the establishment of hydrogen production facilities (see Figure 8). The availability of favourable business models for hydrogen exploration and clarity on plans for infrastructure development, coupling production to end use applications, will be important in supporting decision making and accelerating the establishment of these early stage initiatives. The development of clear routes to market will be essential to maximise the potential of a national hydrogen production pipeline.

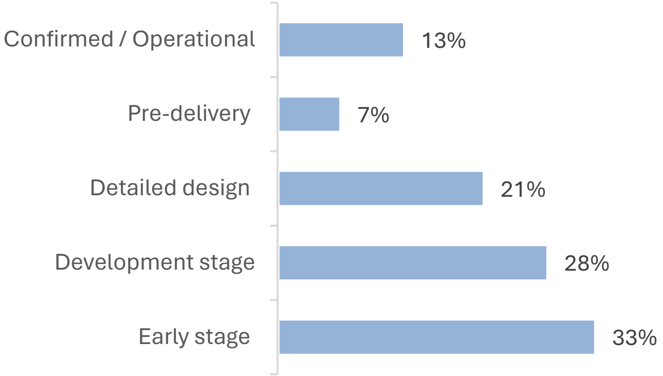

Figure 7: Project development stage

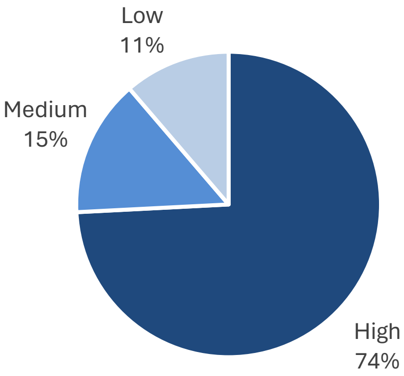

Figure 8: Commitment to $H_2$ production

## 3. Export ports and possible transport vectors

The UK's extensive offshore infrastructure and well-established supply chains across the energy sector can be adapted or repurposed to support hydrogen distribution (see Figure 9). These adaptations can reduce cost and extend the economic lifetime of existing hydrocarbon terminals and ports.

The selection of sites for hydrogen export either via pipeline or through shipping must take into consideration port size, existing infrastructure and ability to accommodate export vessels safely, as well as proximity to wind resource. Plans for hydrogen distribution networks in the UK and in Europe should be coordinated to ensure efficiency in port adaptation and to maximise infrastructure reuse opportunities.

Any ship-based approach to hydrogen export requires pre-treatment of hydrogen, with ammonia and LOHC requiring the most significant chemical conversion steps. Taking into consideration the energy intensity associated with these conversion processes, choosing industrial sites where similar processes already take place yields more benefit than opting for the development of greenfield sites.

Figure 9: Hydrocarbon terminals in Scotland

### 3.1 Export Ports

**Sullom Voe Terminal**

The Sullom Voe terminal on Shetland supports the operations of oil basins to the East and West of Shetland. The terminal has been in operation since 1981, with hydrocarbon production activities expected to continue through to 2045.

The Shetland region has outstanding offshore wind resources, with the highest average wind speeds in the UK. Reliance on grid connections to mainland is limited and could lead to a large number of stranded assets, so the development of curtailment options such as production of green hydrogen or hydrogen derivatives at industrial scale is a priority. A 600 MW HVDC interconnector is being commissioned to accommodate future wind generation and expected to be operational by 2025. Industrial land available could easily accommodate the production and handling of hydrogen and derivatives, providing favourable conditions for the development of a well-connected clean energy hub.

Sullom Voe is a deepwater port currently equipped with three tanker loading jetties designed for crude oil export in ultra-large tankers (up to 350,000 DWT) and a fourth jetty designed for oil and LPG export in medium range tankers (up to 80,000 m$^3$).

**Flotta Terminal**

Located on Flotta Island in Orkney, the Flotta terminal covers a 395 -acre site commissioned in 1976. Crude oil can be imported into the terminal from local offshore installations through a 210 km subsea pipeline and a jetty is available, admitting crude oil and LPG vessels up to 170,000 DWT.

The installation of a 220 MW HVDC interconnector has been approved and there is also potential for a refuelling station within the terminal, servicing hydrogen-powered shipping. Significant industrial space is available in the vicinity of the terminal which could be used for hydrogen production, with plans for an export-ready green hydrogen hub under development. [49]

**Stornoway Deep Water Port**

Stornoway port, the primary port in the Outer Hebrides, is currently being redeveloped to establish a deep water terminal with 800 m of quay at 10 m water depths, a new berth to accommodate vessels up to 360 m long and significant laydown area for the wind sector and industrial use. A haul route is also planned to facilitate transport of large components from the offshore renewables engineering industry at Arnish.

Renewable power connections will be established in the port making use of local supply and LNG and other fuel storage facilities will be available for vessel supply. The diversification of port operations aims to drive socio-economic development in the region.

**Cromarty Firth**

The Cromarty Firth has provided services for the oil and gas industry since 1973 and more recently has become an important hub for the offshore wind industry due to its location close to several offshore wind development areas in the North East of Scotland.

This port houses six marine facilities, encompassing over 2,000 m of quayside at up to 14 m water depth as well as sheltered anchorage at up to 30 m depth. The Inverness and Cromarty Firth Green Freeport consortium is a partnership of public and private sector organisations aiming to establish a major hub for green energy in the region. The acquisition of Green Freeport status, confirmed in January 2023, is expected to attract investment into offshore wind assembly and production facilities as well as advancing plans for local hydrogen production and distribution infrastructure.

**St. Fergus Gas Terminal**

The St. Fergus Gas Terminal is located on the northeast coast of Scotland and was commissioned in 1977. St Fergus is the central gathering hub for gas production from the Northern North Sea region, housing the SEGAL system and the SAGE gas terminal, which connect to a number of fields from both UK and Norwegian sectors.

The Acorn Hydrogen project aims to produce hydrogen by SMR with CCS in a site adjacent to St Fergus gas terminal, with emitted $CO_2$ transported to Acorn’s permanent geological storage. St Fergus terminal is well connected to the nearby Peterhead Port, a deepwater port that has the potential for export of hydrogen through shipping.

### Grangemouth / Hound Point

The Grangemouth refinery is situated on Scotland's east coast and has a refining capacity of 150,000 barrels per day. The refinery is connected to the Forties Pipeline System for oil intake from the North Sea and to Finnart Ocean Terminal for oil import and products export. Oil export is processed through the nearby Hound Point marine terminal, made up of two berths with capacity to load tankers up to 350,000 DWT. Considering the existing petrochemical manufacture capability, Grangemouth could be well placed for the production of ammonia for export.

## 3.2 Transport Vectors

Pure hydrogen can be transported either as compressed gas ($GH_2$) or as cryogenic liquid ($LH_2$). To facilitate transport, hydrogen can be converted to a derivative form such as ammonia, synthetic natural gas or LOHC. Transport at scale can be achieved through pipeline or by ship, with road transport feasible at smaller scales.

### Gaseous hydrogen

Gaseous hydrogen production is increasing steadily in Scotland. Truck or rail transportation of gaseous hydrogen is currently a very expensive option. Pipelines provide the most cost-effective solution and there are several projects underway focused on the development of pipeline-based networks for hydrogen transport across Europe. Scotland's existing offshore infrastructure (Figure 10) can facilitate the development of export options to Europe through pipeline repurposing. Although the repurposing of gas transport infrastructure for hydrogen is only in the early stages of planning, the co-location of hydrogen production with export helps minimise the transport requirements, making it more likely that small dedicated pipelines are developed connecting production hubs to the nearest export location.

A centralised approach to production of hydrogen paired with cross-border transportation via pipeline appears to be the most efficient approach to hydrogen transportation, however the high capital investment associated with the commissioning of pipelines makes this option unlikely to be deployed in the early stages of development of a hydrogen economy.

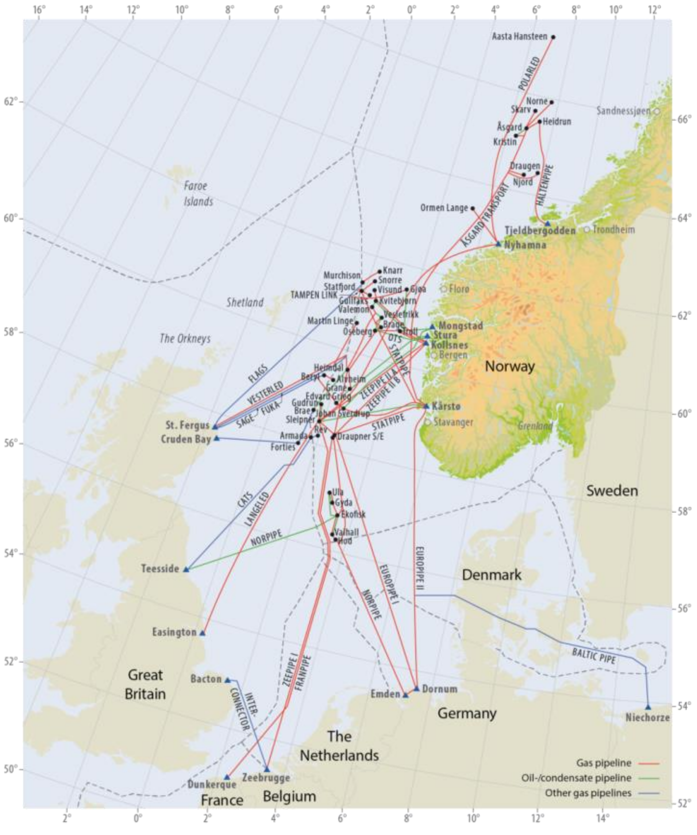

Figure 10: North Sea O&G pipeline network. [93]

### Liquid hydrogen

The transport of hydrogen in liquid form using tankers is more affordable than transport in gaseous form using tankers due to a higher gravimetric and volumetric density, but temperatures of -253 °C are required which involves a significant energy demand and introduce challenges relating to cryogenic risk.

### Ammonia

Ammonia provides an alternative to the transport of high purity hydrogen transport, with advantages over liquid hydrogen transport due to the well-established nature of ammonia shipping. Ammonia is an ideal carrier due to its ability to store a high volume of hydrogen and can be transported at temperatures of – 33 °C or pressures above 10 bar utilising the same vessels used for LPG transport. Production is energy intensive but the process is well suited to electrification and the use of ammonia directly as feedstock is especially cost-effective.

### Synthetic Natural Gas

SNG provides a seamless alternative to fossil natural gas thanks to the ability to transport and store using the same infrastructure without the need for adaptations. Production of SNG from Hydrogen and $CO_2$ provides a clean fuel option with a fast route to market. Currently, there are no plans for SNG production nationally.

### Liquid Organic Hydrogen Carriers (LOHC)

LOHCs provide an option for storage and transport of hydrogen in liquid form at ambient temperature, enabling the use of conventional liquid tankers. An energy intensive hydrogenation process is required prior to transport, followed by dehydrogenation at the import point to regenerate both the hydrogen and the carrier compound which is then reused.

# 4. Storage and transport options

Storage solutions are an important element in ensuring the reliability and flexibility of energy systems with large amounts of intermittent sources, maintaining the balance of supply and demand. Hydrogen molecules are light and of a low density, posing challenges in regards to storage. Adaptations are required to ensure an increase in density suitable to the storage conditions.

## 4.1 Subsurface storage of hydrogen

### Salt Caverns

Salt caverns are cavities created artificially in salt deposits, composed of extremely tight rock mass well suited to gas storage. They provide storage volumes from 200,000 $m^3$ to 800,000 $m^3$ and keep about a third of the gas storage volume as cushion gas, which is a relatively low proportion. Salt caverns allow for the storage of hydrogen at pressures of 100 to 275 bar. [73] Since only a small footprint is required above ground, they provide a low cost storage option for load balancing and trading reserve. [79]

Salt caverns are the only proven form of geological storage for hydrogen. In Teeside, a plant with three small caverns has been in operation for the storage of hydrogen for over 50 years. Halite distribution in the UK is centred on the Cheshire Basine, East Yorkshire and the Wessex Basin, meaning there is no availability of salt caverns onshore in Scotland. [7]

### Depleted Oil and Gas fields

Depleted reservoirs are abundant in Scotland and frequently well equipped with platform and pipeline infrastructure. Geological surveys and operational experience acquired while fields were in operation provide a good profiling of reservoir characteristics. They provide larger storage capacities than salt caverns, but tend to be more permeable which could compromise the purity of hydrogen stored in these conditions (TRL 4). The potential presence of residual hydrocarbons in the reservoir is also a concern as it may require separation from hydrogen upon extraction.

Gas fields with low $CO_2$ concentrations and geologies containing low amounts of carbonate- and sulphate-bearing minerals are preferable for hydrogen storage. Better modelling of the interactions between rock material and stored gases would be beneficial to reservoir suitability assessments.

Options to address buffer storage and small scale inter-seasonal storage include repurposed offshore pipelines (TRL 4), subsea storage tanks (TRL 3) and cryogenic liquid storage tanks (TRL 9)

## 4.2 Transport routes

An essential aspect in the development of a hydrogen market with export capability is the identification of options for distribution from production site to end-use point. Cross-border transport poses particular challenges due to increased distance and potential regulatory differences between the export and import country.

### Pipeline transport

Pipeline transport is the preferred option for gaseous hydrogen transport and it is expected to become a fundamental pathway for hydrogen transport, as it provides a cost-effective and reliable means of transport for large volumes. If transportation costs are accounted for, the supply of green hydrogen via pipeline from Scotland to European markets could be comparable to other sources of hydrogen globally. As a capital intensive option, pipeline infrastructure is unlikely to be commissioned prior to the 2030s.

NZTC's Hydrogen Backbone Link project performed an assessment for the routing of a pipeline dedicated to the transport of gaseous green hydrogen from Scotland to continental Europe (see Figure 11). Both re-use and new build infrastructure were considered assuming a 10 GW capacity. The option to create an entirely new pipeline for transport directly from Scotland's Flotta terminal into Germany's Emden region ranked highest when comparing drivers such as schedule, operability and overall cost.

In addition to the larger bore pipeline connecting these two regions, additional spurs from Sullom Voe, Cromarty Firth and St Fergus enable links to other regions of Scotland where high hydrogen production capability is anticipated, simplifying the delivery of hydrogen to the export terminals. The majority of the proposed pipeline route would transverse the Norwegian and Danish sectors, following most of the northern ScotWind leasing sites as well as a number of German offshore windfarms, which opens up potential connections to wind-powered offshore electrolysers in the future.

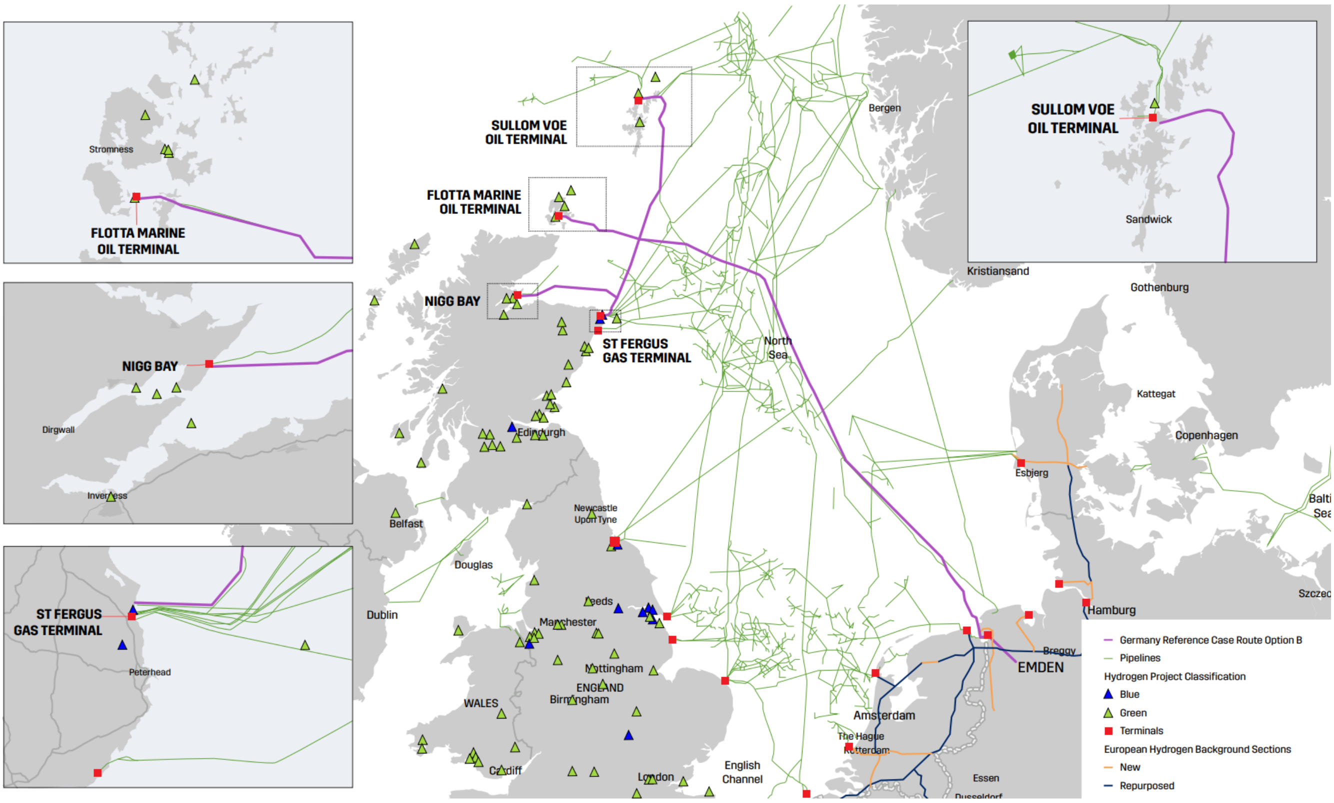

Figure 11: Hydrogen Backbone Link connecting Scottish hydrogen production hubs to Emden in Germany. [88]

The establishment of a hydrogen onshore transport network, as planned in Germany with connections to demand centres and the European network, further benefits the option of pipeline import of gaseous hydrogen. With several offshore hydrogen pipeline projects under planning across the North Sea countries, there is a need for collaboration in the development of hydrogen transportation plans and infrastructure to ensure there is alignment across initiatives.

### Shipping transport

Liquid hydrogen

Hydrogen liquefaction is a well-established process currently used at small scales, mostly for aviation fuel. The transport of liquid hydrogen by shipping tanker is technologically feasible but commercial vessels are still in development and at present involve significant cost. This makes large-scale maritime export unlikely prior to 2030. In Scotland, no plans have been announced for the adaptation of export terminals to suit liquid hydrogen export, but their establishment is likely during the 2030s as commercial vessels become available.

Ammonia

Ammonia production in Scotland is limited at present, but plans are being developed to enhance capability. A low carbon ammonia plant is expected to be commissioned by 2027 as part of the Zero Carbon Humber initiative. The main barrier to the use of ammonia as carrier for hydrogen is the efficiency of the conversion processes.

As demand for ammonia grows, the onshore transport network is expected to develop steadily, with options for train and truck transport already widely available. Although export infrastructure is not currently available in Scotland, there is considerable similarity between LPG and ammonia distribution which minimises the level of adjustment that would be required to enable ammonia export in the short term. Sullom Voe and Grangemouth are well equipped for LPG export and would be suitable for ammonia distribution with minimal adaptation. Offshore transport in liquefied gas carriers is well established, with efficient shipping routes in operation across the globe.

Synthetic natural gas

The export of synthetic natural gas is unlikely in the short term as there are no large-scale production projects in planning. Challenging aspects associated with the production process include production costs and the capture of $CO_2$ for feedstock. Transport of SNG isn’t technically challenging, benefitting from a well-established LNG transport infrastructure available in Scotland, but production facilities aren’t currently planned. Export and transport infrastructure are widely available in Scottish export terminals with minimal adaptation requirements.

LOHC

Although LOHC production processes are well established their application is limited by the efficiency of the dehydrogenation processes, making their use for export unlikely prior to 2030. Where possible, co-location in industrial sites would provide significant cost benefit due to the potential for reuse of waste heat in the dehydrogenation process. Onshore and offshore transport do not pose particular challenges as the requirements for LOHC transport are very similar in nature to those of existing refined petroleum products, meaning existing units could be used for this purpose. In terms of export points, Sullom Voe and St Fergus are best equipped for LOHC handling, with minimal adaptations required.

Cost Analysis

The cost of hydrogen production provides the main share of total expenditure, independently of the type of carrier adopted and associated conversion and distribution costs. Figure 12 provides a comparison of the cost of transport for each hydrogen carrier considered. Transport costs are comparable for most derivative options with the exception of liquid hydrogen where a considerably higher cost is incurred due to the specialised conditions required for safe transportation. The transport of LOHCs has the disadvantage of requiring the return transport of discharged carrier liquid as well as additional storage capacity required for transport.

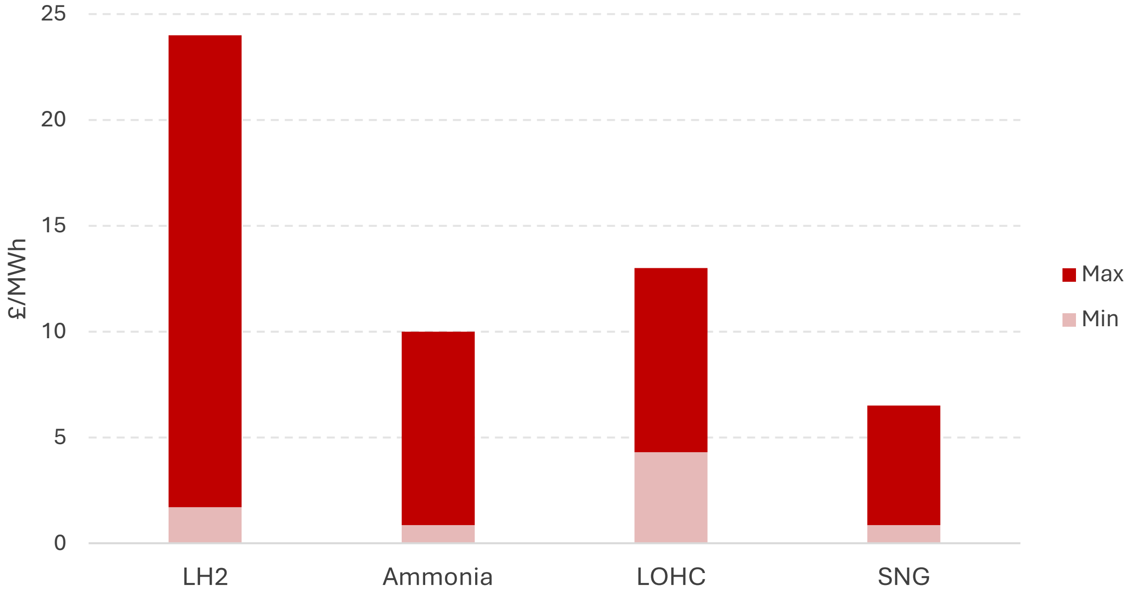

Figure 12: Transport costs for each hydrogen carrier. Average values based on today's cost and expectations for 2030 and 2050, adapted from. [126]

# Hydrogen Demand and Transport in Germany

To provide an overview on the German hydrogen market, this chapter is built as follows. First, an overview of the existing and planned regulatory framework regarding hydrogen demand and transport is provided to set the context. The second section focuses on a meta-analysis of German hydrogen demand by 2050 to provide indications on predicted market size and sector specificities. In the third section, prospective transport routes are analysed to identify feasible options. The structured approach of this chapter ensures a holistic view of the German hydrogen market and maps out the ecosystem within which Scottish green hydrogen must navigate to meet German demand.

## 1. Overview of regulatory framework

The study is set in the context of the following strategies, legislation and initiatives as shown in Table 4. Since all these regulations have an explicit reference to hydrogen transport and demand they are of particular relevance to the study. However, it is important to note that the legislative process has not yet been completed in many areas and is still under development. For this reason, this section can only provide an overview of the status quo and should not be understood as a conclusive analysis.

Table 4: Political and legal framework in Germany

| Instrument | Type of regulation | Status |
|---|---|---|
| National Hydrogen Strategy | Federal Strategy (not binding) | was updated in 2023 |
| Hydrogen Import Strategy | Federal Strategy (not binding) | to be published in 2024 |
| National Port Strategy | Federal Strategy (not binding) | 2024 |
| Carbon Management Strategy | Federal Strategy (not binding) | expected in 2024 |
| LNG Acceleration Act | National Act (binding) | 2022 |
| H2Global | Funding Project (voluntary) | 2022 |
| Hydrogen Core Network | Planning Document (binding) | will be finalised in 2024 |
| Delegated Act on green hydrogen | European Act (binding) | 2023 |
| Hydrogen Acceleration Act | National Act (binding) | expected in 2024 |

### National Hydrogen Strategy

The **National Hydrogen Strategy** [16] ("Nationale Wasserstoffstrategie – NWS") was updated in 2023 and provides a framework for the ramp-up of the green hydrogen economy in Germany. In regard to hydrogen import, transport and demand the update includes:

- an **increase** in the ambition level from 5 **to 10 GW electrolysis capacity** by 2030;
- an increase in hydrogen **demand** from 95 to 130 TWh by 2030 (originally: 90 to 110 TWh).
- The highest demand for hydrogen is seen in the industry sector. In this sector the use of hydrogen is to be supported through various funding projects, e.g. carbon contracts for differences.
- To cover the hydrogen demand around 50-70% shall be **imported** by 2030, mostly by ship-based solutions. **After 2030**, the import shall be expanded to **pipeline-based** solutions.
- The aim is to quickly install an **import infrastructure** in Germany and Europe in order to meet the foreseeable demand for hydrogen. For this purpose, a hydrogen acceleration act is to be drawn up to accelerate the roll-out of the hydrogen import infrastructure.
- In order to connect the import and storage hubs with the relevant customers a **hydrogen core network** is to be fully operational by 2032.

### Import Strategy

To address the particular importance of $H_2$ imports, the NWS 2023 is to be supplemented by an **Import Strategy** for hydrogen and its derivatives. In the short term it is planned to import mainly ammonia. In the medium to long term, imports of green methane, synthetic methanol, LOHCs and liquid hydrogen may play a role. The Hydrogen **Import Strategy** is not yet finalised but is expected to be completed and published in 2024.

### National Port Strategy

The National Port Strategy was published on 20th March 2024. [15] It considers the development of ports into sustainable hubs for the energy transition, climate-neutral shipping and the development of hubs for transport storage as a central field of action. The infrastructure still to be developed for the hydrogen economy plays a central role here. The **further development of ports as logistical hubs for the import of hydrogen and hydrogen derivatives is listed as** a strategic goal. The **measures** identified in relation to hydrogen include:

- the provision of sufficient space for storage facilities where energy carriers are stored and for the production of green energy carriers
- the provision of space and docks required for energy carriers
- strategic planning for the timely creation of the necessary port infrastructure for the landing and onward transportation of hydrogen derivatives
- the **development of an import infrastructure for hydrogen with terminals and pipelines** and onward transportation by water, also taking into account sustainability aspects in accordance with the update of the National Hydrogen Strategy
- the uniform adaptation of the legal framework for the handling, use and transportation of hydrogen and hydrogen derivatives

### Carbon Management Strategy

On February 6th 2024, the European Commission presented a communication on the **Industrial Carbon Management Strategy.** [42] It is part of the EU's communication for its 2040 climate target. The strategy sets out a series of measures to be taken at EU and national level to boost carbon capture, utilisation and storage (CCUS). As it is up to the Member States to decide on the best applications at national level, the EU's Industrial Carbon Management Strategy does not identify specific sectors for the application of carbon capture for permanent storage or further utilisation. Key points for a national carbon management strategy were published by the German federal government on February 26, 2024. [20] For the time being, these are the planned contents of the CMS, which will be discussed and coordinated in further steps before they constitute an official national strategy. The key points paper is currently being coordinated by the ministries. [19] According to the paper, the strategic focus of CCS is on industries with difficult or unavoidable emissions, such as the cement and lime industries (p. 1). With regard to hydrogen, one of the key points presented is the construction of new gas-fired power plants that are converted to hydrogen in order to avoid GHG emissions in electricity generation (p. 2). In addition, industrial processes for which the conversion to electrification or hydrogen is not yet possible in a cost-effective manner are mentioned as an area of application for CCS/CCU. (p. 3f.)

### LNG Acceleration Act

The **LNG Acceleration Act** ("LNG-Beschleunigungsgesetz – LNGG") [13] is also relevant in the context of import terminals. The purpose of the LNGG is to accelerate the construction and commissioning of the LNG terminals referred to in § 2 and the associated transport infrastructure. However, approval may only be granted if the terminal is also capable of importing a hydrogen-based derivative later on. The LNGG stipulates that it shall be possible to convert the terminal to import Ammonia by 1st of January 2044 at the latest. However, an application for a change of permit to import hydrogen carriers other than ammonia may also be submitted up to that date. In this case the conversion permit must be applied by 01.01.2035 at the latest. In addition, the conversion costs must not exceed 15% of the construction costs for LNG terminals. These rules are intended to incentivise the switch to the import of hydrogen-based energy sources. In addition to the conversion of LNG terminals, dedicated $H_2$-terminals are to be built in the short term. Stationary land-based terminals may also be converted to synthetic methane or biomethane if the applicant demonstrates that it is technically feasible to capture, compress and transport carbon dioxide at the terminal site. From this it can be concluded that the landing of SNG is only allowed if reforming to $H_2$ is planned at the terminal. However, neither the provision itself nor the explanatory memorandum to the Act contain an explicit obligation to convert SNG into hydrogen directly at the terminal. Further legislative clarification is required. A **Hydrogen Acceleration Act** is planned to accelerate their implementation. Publication of the draft law is planned during 2024. [16]

### H2Global

In terms of $H_2$ imports **H2Gobal** provides planning and investment security for the development of large-scale electrolysis capacities and transport infrastructure. The tender-based funding instrument H2Global was approved by the BMWK in December 2021 and is being supported with € 900 million for the first tender window. The first tender procedure for ammonia produced by green hydrogen was launched on 30th November 2022. The overarching goal is to support the global market ramp-up for green hydrogen. The idea is to buy green hydrogen products cheaply on the global market and sell them to the highest bidder in the EU. Hydrogen exporters from outside the EU will have security of investment through long-term purchase agreements of ten years, and customers within the EU will have access to green derivatives. Hydrogen derivatives that are considered within the first tender procedure are ammonia, methanol and electricity-based sustainable aviation fuel. The first hydrogen derivatives procured under the H2Global program are planned to be delivered to the EU by the end of 2024. [21]

### Hydrogen core network

For the transport aspect, the **hydrogen core network** will be in place by 2032 and will connect large hydrogen consumers, power plants and import terminals. The routing is based on the integration of: [51]

- IPCEI projects and living lab-projects
- major industrial offtake centres
- planned hydrogen storage facilities
- expected locations of hydrogen power plants
- border crossings with other regions in Europe
- major feed-in and feed-out areas

The German Federal Network Agency (“Bundesnetzagentur – BnetzA”) is currently analysing the draft of the core network submitted by the TSOs earlier this year. The TSOs will take the results into account in their final joint application for the core network. The deadline for submitting the joint application for the core network has been extended by the BNetzA to 21st May 2024. Further information on the hydrogen core network are presented in chapter 3.1 (section “Onshore: Hydrogen network”).

### Delegated Act (RED II)

On 10th February 2023, the European Commission adopted the **Delegated Act** [51] to specify the requirements for the production of green hydrogen and its derivatives. This act, derived from the Renewable Energy Directive, mandates that all EU member states increase the share of renewable energies to 14% by 2030. Green hydrogen and its derivatives, classified as renewable fuels of non-biological origin, can contribute to this target if they fulfil the criteria outlined in the Delegated Act. The requirements apply to both domestic producers within the EU and international producers exporting renewable hydrogen to the EU. In order to increase the marketability of hydrogen and derivatives within the EU, exporters should observe the criteria of the Delegated Act. [23]

The Delegated Act stipulates that green hydrogen can be produced through one or more of the following production pathways:

- from a Renewable Energy Source (RES) transmitted through a direct connection, provided the RES facility is no older than 36 months at start-up of the RFNBO facility (with extended periods for certain expansions) and where no power is taken from the grid;
- from grid-sourced electricity where RES power would otherwise be curtailed without the RFNBO production (proof of this needs to be obtained from the national TSO);

- from grid-sourced electricity where the share of RES production exceeds 90% in the relevant electricity market "bidding zone" as an average of all consumption in the previous calendar year;
- from grid-sourced electricity where the grid average GHG emissions intensity is below 18 g $CO_2e$/MJ. This favours production in countries with high penetration of nuclear power (as well as RES). The RFNBO producer must enter into a renewables PPA (but the RES generation facility need not comply with the additionality test) and satisfy the temporal and geographical requirements described below;
- from grid-sourced electricity where each of the following criteria are satisfied:
    - *Additionality:*
      The RFNBO producer has entered into a PPA (directly, or via intermediaries) with one or more RES producers and such RES generation facility is no older than 36 months at start-up of the RFNBO facility (again, additional periods for expansions);
      The RES generation facility has not received any State aid (i.e. this restricts a broad category of subsidies and state support, subject to certain exceptions).
      These two requirements above will apply from 1 January 2028, except for RFNBO facilities commencing operations before that date, in which case they will only apply from 1 January 2038. They will, though, then apply in full even to pre-existing RFNBO producers. This raises the possibility that, in certain cases, a RFNBO facility may need to change its RES power supply solution in the middle of operations once these rules kick-in.
    - *Temporal correlation:*
      The production of RFNBO must take place within the same calendar month (until 1 January 2030), or, thereafter, within the same one-hour period as the production of electricity from the contracted RES generation sources.
      This one-hour period could make pure solar powered RFNBO production projects, and many wind-only projects, too expensive (since they will not be capable of operating 24 hours a day).
    - *Geographical correlation:* The RFNBO and RES facilities must be located within the same, or in an interconnected, electricity market bidding zone.

# 2. Analysis of German hydrogen demand 2030-2045

Germany's current annual hydrogen demand of 55 TWh is primarily derived from various industrial processes. These include 21.3 TWh from the desulphurisation of conventional fuels in refining, 20.6 TWh from ammonia production plants, and 4.7 TWh from methanol production plants. Notably, hydrogen in these industries is predominantly produced via steam methane reforming (SMR). [41]

Considering the variety of studies with different focuses leading to diverging predictions for hydrogen demand in Germany, a metanalysis is conducted in the first section below. In addition, the currently announced supply and demand projects are analysed to complement the top-down approach considered in the metanalysis. Furthermore, possible applications for hydrogen and its derivatives in Germany are analysed.

## 2.1 Meta-analysis of sector-focused studies

### 2.1.1 Methodology

In order to provide an overview of the estimated hydrogen demand in Germany, a literature research was conducted. Based on the selection criteria shown in Table 5, the following literature has been selected and analysed. The focus is mainly set on system studies with intermediate steps by 2030, 2040, 2045 and 2050. A key requirement for the study selection was the publication date, which should not be prior to 2021. Additionally, studies considering the sectors of industry, transport, buildings and power were selected.

Table 5: Selection criteria for the metanalysis

| | |
|---|---|
| **Type of studies** | Focus on system studies that cover demand side |
| **Geographic scope** | Focus on Germany |
| **Timeframe** | From 2030 to 2050 |
| **Actuality of studies** | Publications from 2021 onwards |
| **Sectoral breakdown** | Industry, transport, building and power |

Table 17 in the appendix provides an overview of the main study contents of the considered literature. A total of 8 studies was analysed. 3 studies were published in 2023, 5 studies in 2021. The majority of these studies focus on projections for the year 2045, in line with Germany's aim to achieve climate neutrality by then, with an interim target set for 2030. Notably, the European Hydrogen Backbone study extends its projections to 2050 to coincide with the European Union's goal of achieving climate neutrality by then.

Furthermore, announced supply projects are analysed to provide a bottom-up perspective and further insights about ammonia and liquid hydrogen are provided.

### 2.1.2 Demand evaluation

Figure 13 offers a comprehensive overview of study results concerning the demand for hydrogen and synthesis products across various sectors in Germany, including industry, transport, buildings, and power. Detailed numerical breakdowns for each sector are provided in Figure 33 within the appendix.

In the **building sector**, most studies project minimal to no hydrogen demand by 2030, primarily relying on heat pumps for heating purposes. By 2045, a slight increase in hydrogen demand is anticipated, with the Ariadne study projecting the highest demand at 68 TWh, contingent upon abundant hydrogen production or importation. According to this study the heating systems and distribution networks must be successively converted to hydrogen in some areas and are operated with e-methane in a few cases.

In the **power/energy sector**, the necessity of a coal exit for climate neutrality, as highlighted by Agora, leads to a significant demand for hydrogen. Analogously to the building sector, demand projections vary depending on the analytical direction of the study. For instance, the S4C-KN study, focusing on power-heat applications, estimates a low-end hydrogen demand of only 28 TWh for 2045.

All studies anticipate a demand for hydrogen in the **transport sector**, with projections ranging from 10 TWh or less in 2030 to a range of 20 TWh to 178 TWh by 2045. The most important application for the future is considered the fuel cell. The Ariadne study forecasts the highest demand, particularly emphasising the challenges of electrifying heavy modes of transport such as ships and aircraft over long distances.

All industries must significantly reduce their $CO_2$ emissions to achieve climate neutrality by 2045. An effective strategy to achieve this goal is to convert industrial processes to hydrogen, which is particularly beneficial for processes that require high temperatures, such as steel production. As a result, hydrogen demand in the **industry sector** is expected to grow steadily until 2045. Notably, the LFS - T45-H2 study projects the highest hydrogen demand of all studies, underlining the key role of hydrogen in the decarbonisation of industrial activities.

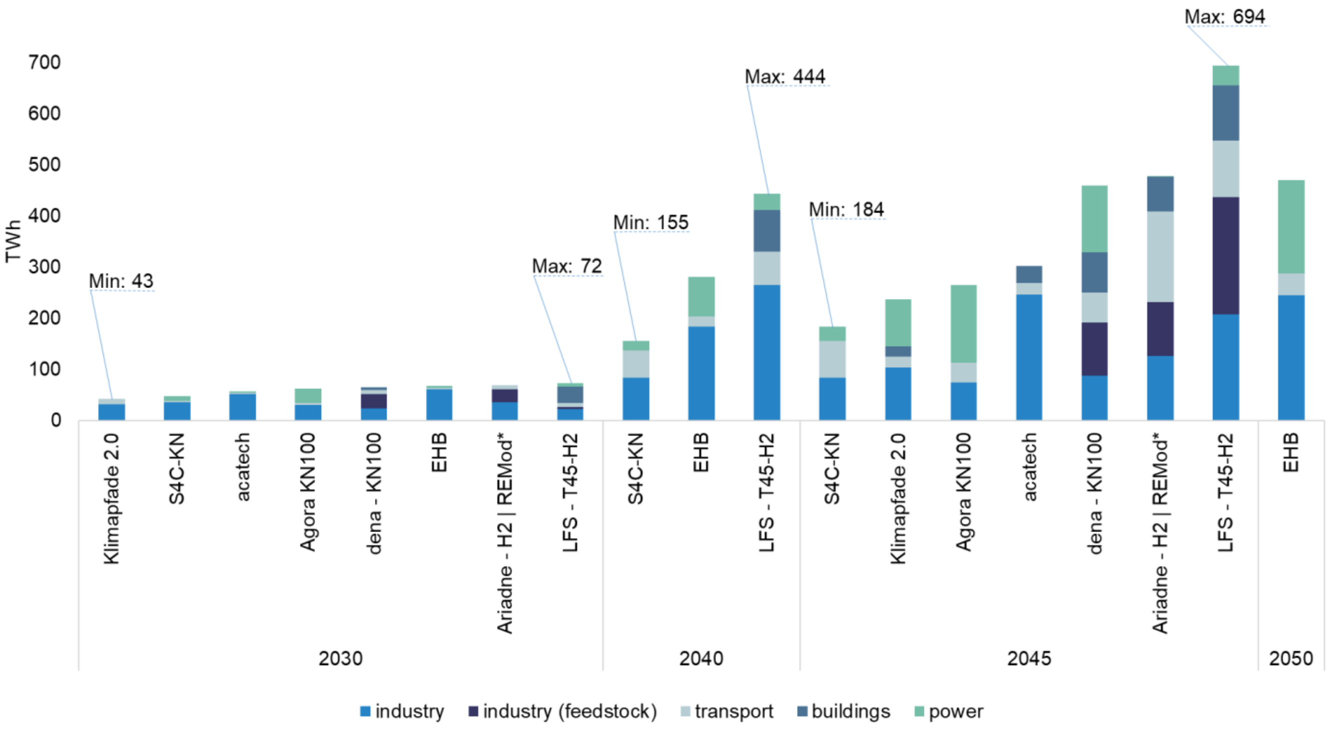

Figure 13: German hydrogen demand from 2030 to 2050 (Own illustration based on considered studies)

In order to provide an overview of the varying demand projections across studies, the available data is interpolated using key years 2030, 2040 and 2045 as shown in Figure 14. For each year the minimal, maximal and mean values are determined.

In line with its commitment to environmental sustainability, Germany has set ambitious goals to eliminate coal usage by 2030, transitioning entirely to renewable energy sources. Projections for hydrogen demand in 2030 vary between 43 to 72 terawatt-hours (TWh). Germany plans to phase out coal in 2030 and thus switch to 100% renewable energies.

- According to Agora, the first gas-fired power plants will be running on hydrogen by 2030.
- The long-term scenarios assume that the transition to green hydrogen use and the overhaul of current processes will kickstart 2030.
- Conversely, Ariadne presents a slightly different perspective, suggesting that from 2030 forward, there will be a narrowing focus on the role of hydrogen in the energy mix.

Noteworthy is that the National Hydrogen Strategy (NWS) forecasts a higher hydrogen demand for 2030 (95 to 130 TWh). The NWS strategy includes the forecasted demand for hydrogen derivatives such as ammonia, methanol or synthetic fuels and is in line with several studies that predict emerging green hydrogen demand in Germany between 40 and 75 TWh. Added to this is the existing grey hydrogen of around 55 TWh. This latter demand will vary based on production changes and is therefore linked with uncertainties.

Beyond 2030, demand consistently rises, resulting in a widening range of estimates across studies. By 2045, the disparity between the lowest and highest projected demand reaches 510 TWh. This variance is attributed to several factors:

- Segmentation of the industrial sector into energetic and feedstock material and energy hydrogen demand in certain studies. For example, excluding non-energetic hydrogen, the total demand for the T45-H2 study would decrease from 694 TWh to 465 TWh.
- Uncertainties surrounding the transition to hydrogen and differences in underlying scenarios and methodologies further contribute to variations in forecasts. For instance, higher ambitions for emissions reduction are found to correlate with increased hydrogen demand.

- Ratio between electrification and hydrogen use in the sectors is also an influencing factor.
- Differences in model design parameters, such as technology costs and energy prices, contribute to varying demand projections.

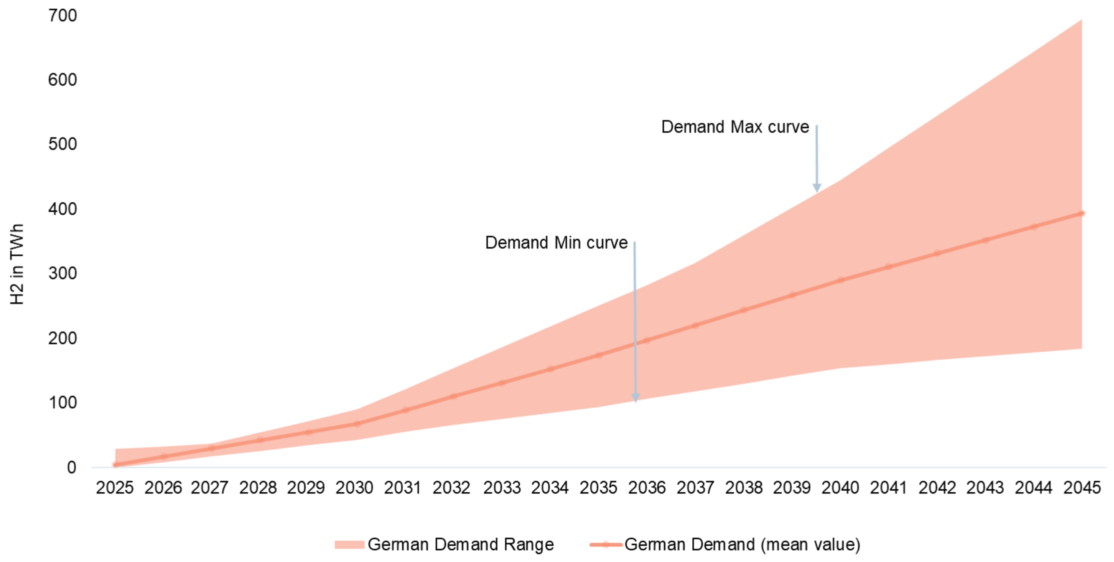

Figure 14: German hydrogen demand range up to 2045 based on analysed studies

Figure 15 provides a detailed breakdown of the industrial sector within the LFS-T45-H2 study. In this sector, the basic chemical industry exhibits the highest demand for hydrogen, followed closely by the steel industry. In the chemical industry, hydrogen is primarily utilised to produce essential compounds such as ammonia, methanol, and high-value chemicals (HVC), all of which contribute to hydrogen use as a feedstock. Conversely, the steel industry primarily requires hydrogen for its energetic properties.

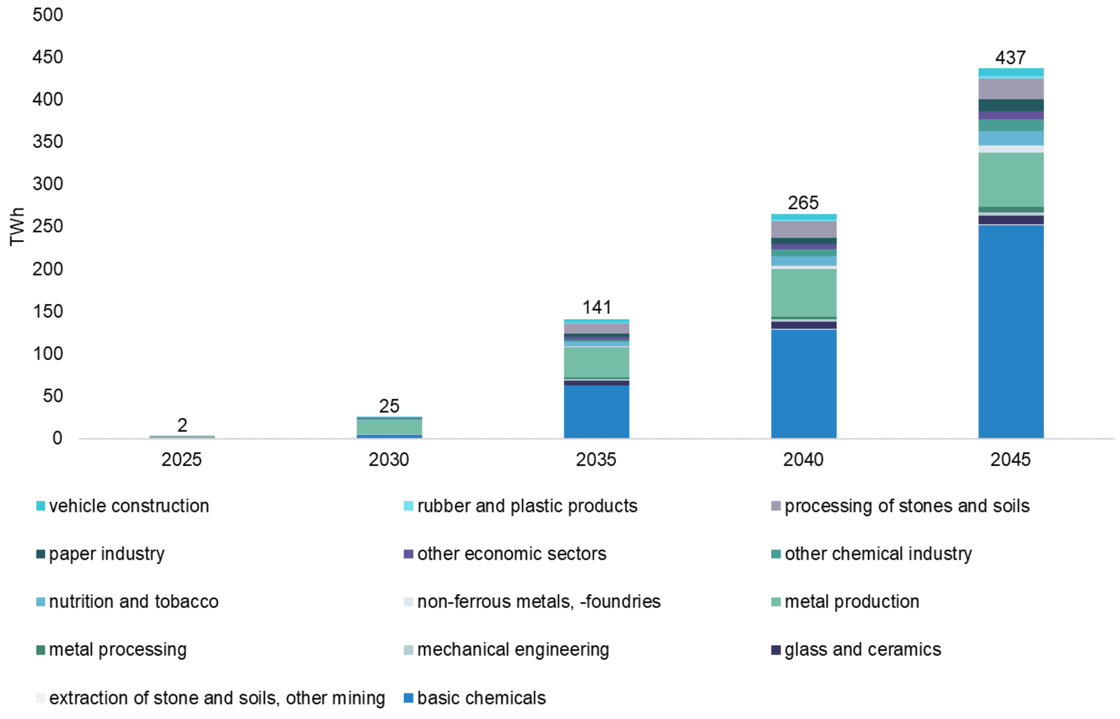

Figure 15: Hydrogen demand in industry [40]

Overall, the hydrogen demand in Germany is notably high, with numerous production projects in the planning stages. However, these initiatives will likely cover only a portion of the overall demand. Figure 16 illustrates Germany's projected domestic production capacity alongside its import requirements. Analysis of six studies indicates that by 2030, the results are largely consistent. Domestic production ranges from 19 to 55 TWh and import requirements range from 0 TWh to 46 TWh. However, the dependency on imports is projected to escalate considerably over time.

By 2045, the studies suggest that imports could vary from 78 TWh to as much as 422 TWh, whereas Germany's own production could span from 72 to 272 TWh. Overall, the projected imports are up to 1.5 times greater than domestic production capacities.

Delving into the specifics of these studies, one particular study forecasts a higher level of domestic production by 2045. This outlier is attributed to a combination of factors: it projects the lowest hydrogen demand for 2045, anticipates lower conventional electricity demand, and expects high outputs from renewable energy sources, enabling more domestic hydrogen production. Additionally, this scenario benefits from a high degree of load-side flexibility, facilitated by robust outputs from power-to-heat plants in heating networks with heat storage, alongside flexible operations of electrolysers.

On the political level, Germany's national hydrogen strategy anticipates that by 2030, between 50 to 70% of its hydrogen requirements will need to be met through imports.

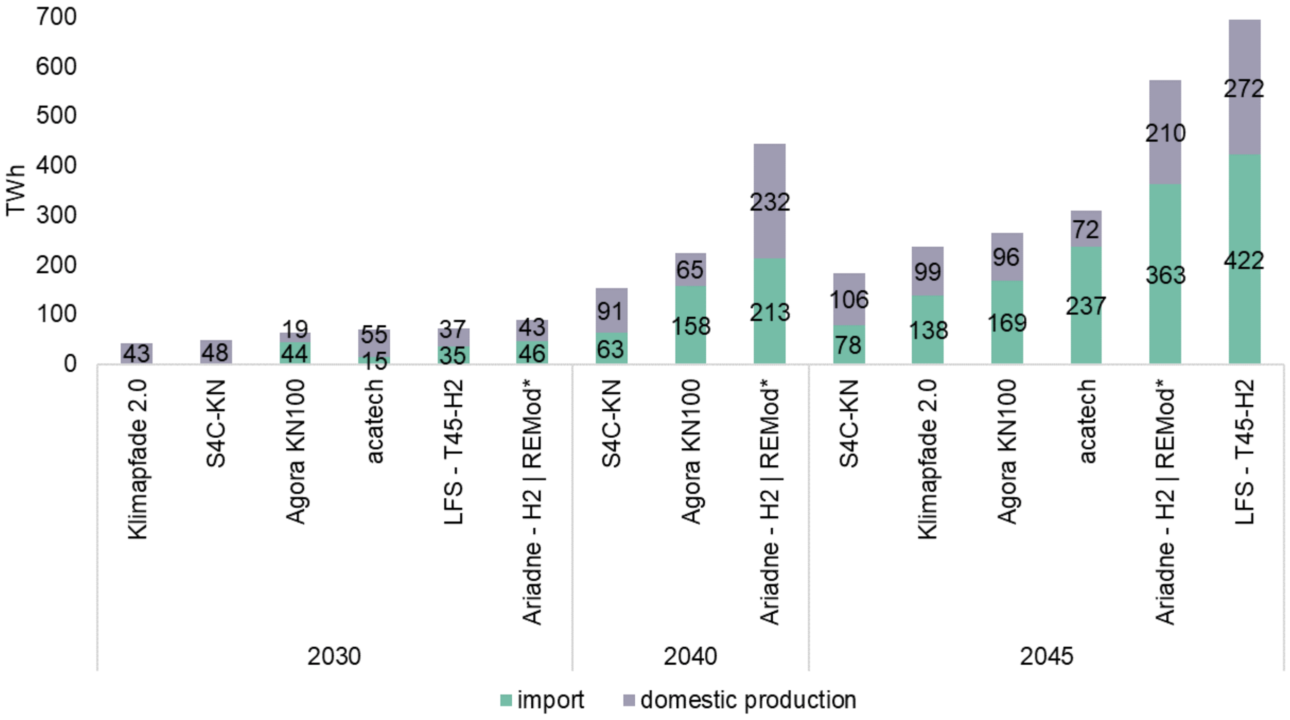

Figure 16: Import and domestic production of hydrogen in Germany (Source: Own illustration based on the studies considered)

Figure 17 shows the range for German import volumes varies between 0 TWh and 46 TWh in 2030 and between 78 TWh and 422 TWh in 2045 depending on the assumptions made in the studies. Scottish export volumes offer the potential to meet part of German import demand in 2030 and even more by 2045. Prospective Scottish hydrogen exports could potentially satisfy 22 to 100 % of Germany’s hydrogen import volume in 2045.

In 2030, the projections from the studies are more aligned, with two studies suggesting that Germany could meet its hydrogen demand entirely through domestic production. The reason for this is mainly the pursuit of national energy independence. In the S4C-KN study, this is based on the fact that electricity from renewable energies will be readily available for electrolysis in 2030. This in turn is due to a combination of a high expansion of renewables and moderate electricity demand.

By 2045, however, the disparity in projections widens significantly, reflecting the effect of differing assumptions across the studies. For instance the Climate Pathways 2.0 study highlights a scenario where the total hydrogen consumption markedly surpasses Germany's potential for generating renewable electricity, indicating a substantial reliance on hydrogen imports. Similarly, the acatech study assumes that imports could account for up to 80% of Germany's hydrogen supply. This projection is contingent upon the availability of electricity from renewable sources and the fluctuating import prices for hydrogen.

Collectively, these studies underscore the complexities and uncertainties in forecasting Germany's future hydrogen economy, while emphasizing the pivotal role of imports as the country advances towards its energy transition goals.

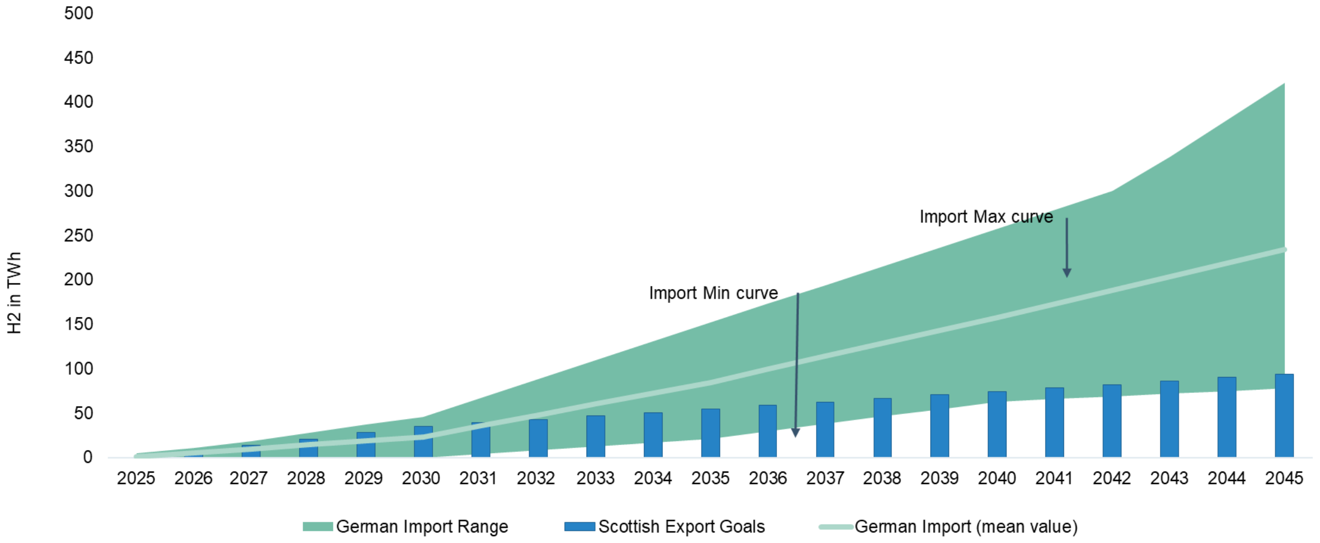

Figure 17: German hydrogen import range up to 2045 based on analysed studies

## 2.2. Announced supply and demand projects

To further supplement the meta-analysis mainly assessing top-down studies projecting hydrogen demand, an examination of announced supply and demand projects is conducted. Through a diligent review of both public announcements and existing literature, a total of 145 distinct projects have been identified. Figure 18 provides an overview of currently planned supply and offtake projects in Germany.

Of the projects pinpointed, 56 are identified as demand-oriented, whereas 89 are focused on the supply side, with a significant portion of these being electrolysis projects.

The demand-side projects span across four key sectors, illustrating the diverse applicability of hydrogen as an energy vector. These sectors include industry, with 33 projects, highlighting its leading role in integrating hydrogen technologies. The mobility sector follows with 21 projects, demonstrating the growing interest in hydrogen-fuelled transportation. Additionally, singular projects in both the infrastructure and buildings sectors indicate emerging use cases, albeit on a smaller scale at this stage. Understandably, these projects represent early adopters with some slated to commence hydrogen use in the short term.

The German Energy Agency (Dena) provides a further analytical layer by estimating that a selection of these projects could generate a cumulative demand of between 50 and 60 Terawatt-hours (TWh). [34] This projection is vital for understanding the potential scale of hydrogen use in the near term and underscores the significant role these early adopter projects could play in shaping the hydrogen economy in Germany.

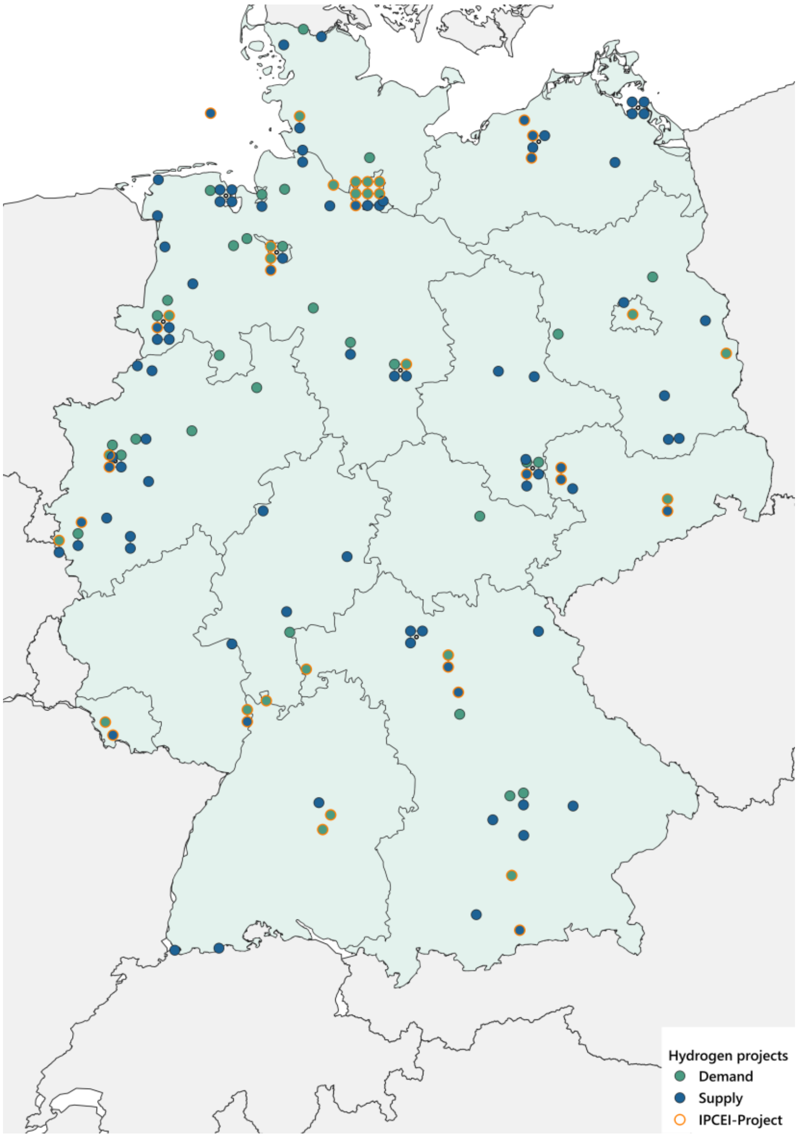

Figure 18: Overview of announced demand and supply projects in Germany[3] [17, 34]

## 2.3. Analysis of hydrogen derivatives' applications

In this section, the potential applications of hydrogen and its carriers are analysed including ongoing developments and expected progresses.

### Gaseous Hydrogen

$GH_2$ is gaining traction as a clean energy source in Germany, particularly in industries aiming for decarbonisation. Its versatility makes it suitable for a wide range of applications, including transportation, energy storage, and industrial processes. Most studies focus on gaseous hydrogen demand in their evaluation. Further information on current announcements and the projected hydrogen core network in Germany can be found in section 3.1.1.

### Liquid hydrogen

Based on cruh21's network activities in Northern Germany, there is considerable activity regarding the import and demand of liquid hydrogen within the region. Several players are investigating the potential of liquid hydrogen and collaborating to derive viable business cases. The demand for liquid hydrogen is driven by its advantageous characteristics, including high gravimetric and volumetric densities (e.g. aviation and maritime sector), high purity (e.g. generators powered by fuel cells as well as semiconductor

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[3] based on large-scale supply and demand hydrogen projects selected for IPCEI funding and dena hydrogen map; no guarantee on completeness.

industry), and compatibility with low-pressure storage systems (e.g. hydrogen filling stations). End-users across sectors such as aviation, maritime, transportation, and industrial applications stand to benefit significantly from these properties. [6, 125]

In Northern Germany and the Hamburg region, the aviation and maritime sectors emerge as significant drivers of $LH_2$ demand. For instance, Airbus has announced plans to launch an aircraft powered by a hydrogen fuel cell system by 2035. Hamburg Airport and the German Aerospace Centre have developed a roadmap for hydrogen utilisation at medium-size airports. The market launch of $LH_2$ demand at airports would take place between 2035 and 2040, followed by the market ramp-up with increasing $LH_2$ beyond 2050. [3, 37] Furthermore, Daimler Truck and Linde have developed a new subcooled liquid hydrogen ($sLH_2$)- refuelling technology for liquid hydrogen. Their aim is to establish $sLH_2$ as refuelling standard for hydrogen-powered trucks and to develop a comprehensive refuelling infrastructure. This would be a basis for bringing hydrogen into logistical supply chains covered by trucks. A 40 t truck would refuel 80 kg of $LH_2$ and has a range 1,000 km. [29]

Research projects „AppLHy!“[4] and “HyLiq”-pilot[5] are also underway to address future demand and applications and conduct research on highly efficient storage and distribution of $LH_2$ on a supra-regional level. [14, 113, 125]

In conclusion, the collaborative efforts of industry players and ongoing research projects suggest a strong likelihood of increasing $LH_2$ demand in Germany, driven by the need for clean and sustainable energy solutions across various sectors.

### Ammonia

Currently, ammonia is primarily used in fertiliser production and refineries, but also as a basic chemical in various industrial processes. In future, the potential extends to utilisation in ship engines, industrial processes or power plants and the possibility of reconversion into hydrogen. Presently, in Germany, four plants in Brunsbüttel, Wittenberg, Cologne and Ludwigshafen are producing Ammonia with a total estimated production volume of 3.1 Mt/a. Due to the high energy prices in Germany, BASF recently announced that it would shut down one of the two ammonia production facilities at its main plant in Ludwigshafen and relocate production to the USA. [40]

In 2022, EY analysed that Germany will have an ammonia demand of 3.7 Mt. by 2030 considering only the existing markets. [10]

By 2050, EY estimates a total ammonia demand of 11.5 Mt, with 5.5 Mt from existing markets and further 5.8 Mt. for new ammonia markets. [48]

Sevel studies show that the direct import of green ammonia by ship is cost-effective compared to the domestic production of ammonia from domestically produced or imported hydrogen in 2030. [84] Ultimately, market dynamics will play a significant role in determining the setup and quantities involved in the ammonia export to Germany, especially since there are varying ranges for ammonia demand.

### Synthetic Natural Gas

SNG serves as a versatile energy solution, seamlessly integrating into existing natural gas infrastructure for grid injection, heating applications, power generation, and transportation fuel. Its ability to supplement natural gas during peak demand periods and offer a cleaner alternative in sectors reliant on fossil fuels makes this a flexible transition fuel option.

### Liquid Organic Hydrogen Carriers

LOHCs cannot be used directly as an energy source. LOHCs serve as a means of storing and transporting hydrogen in a liquid form, but they require a separate process to release the hydrogen for use as an energy carrier. For import use, these dehydrogenation units are stationary. For a wider range

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[4] Part of flagship project “TransHyDE” funded by the Federal Ministry of Education and Research (BMBF)

[5] Consortium of TU Dresden, IFW Dresden, HTW Dresden and SciDre GmbH; part of flagship project “TransHyDE” funded by the Federal Ministry of Education and Research (BMBF)

of applications there are development projects for mobile units, e.g. in the marine sector, for on-board propulsion systems, coupling LOHC storage systems and hydrogen fuel cells. [63]

# 3. Prospective transport routes

With reference to the previous outcomes on hydrogen demand development, tis section focuses on how hydrogen supplied from Scotland can be transported, imported and distributed to demand sites within Germany.

Based on the introduced supply chains (cf. Supply chain overview), for each form of hydrogen and derivative the following three steps are considered:

- Offshore transport: Transporting hydrogen and its derivatives across the North Sea from Scotland to Germany
- Import infrastructure: Importing hydrogen and its derivatives via import terminals or pipeline landfalls into Germany
- Onshore transport: Transporting hydrogen from import terminals or landfall points to demand sites within Germany

The focus is set on technological feasibility including infrastructure availability, developments and technology readiness levels (TRL)[6] along the supply chain of each form of hydrogen and derivatives. The analysis is based on a literature review, expert interviews and a compilation of announcements of infrastructure projects and initiatives in Germany.

In addition to the production, distribution and utilisation of hydrogen, hydrogen storage will also be considered as a system element. Currently, several uncertainties exist regarding the role of hydrogen storage in the hydrogen infrastructure ramp-up. According to a consultation conducted by the BMWK the entire market environment is still characterised by significant uncertainty, namely regarging the role of hydrogen storage, demand for storage capacity, financial models for development and repurposing of hydrogen storage and questions concerning market frameworks and balancing. The development of a German hydrogen storage strategy is anticipated by the middle of 2024, aiming to set a regulatory framework to provide planning reliability. [36] Due to the uncertainties regarding future hydrogen storages in Germany, this topic is not included in the scope of this study.

## 3.1. Gaseous hydrogen

Looking at the characteristics of gaseous hydrogen (Supply chain overview), two common transport options have emerged – transport by pipeline or by mobile storage units on ships, trains, and trucks.

Pipeline connectivity allows the transport of gaseous hydrogen via long distances and in large quantities, whereas mobile transportation guarantees supply to demand sites without pipeline connection depending on the means of transport in rather small or medium quantities.

It seems likely that gaseous hydrogen transport by a pipeline network, either repurposed natural gas pipelines or new built hydrogen pipelines, will be one of the essential transport paths in the coming years. Plans for an onshore hydrogen core network including an offshore pipeline in the German North Sea would seem to confirm this. The German hydrogen core network is to be built by 2032, starting in 2025 and with some sections becoming operational from 2027 , and will enable long-distance transport. Onshore and offshore transport with mobile storage units for compressed gaseous hydrogen is already established for small volumes.

The following two sections will consider pipeline and mobile transport options in more detail.

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[6] Technology readiness level based on the definition of the European Commission [46].

### 3.1.1 Transporting hydrogen via pipelines

There are a few existing hydrogen pipelines in Germany used for industrial purposes. The longest hydrogen pipeline with a 240 km length is installed in the Ruhr region, connecting the chemical production hub in Marl with distant off-taking plants. In the “Central German chemical triangle” there are several hydrogen pipelines with a length of 150 km in total, and in Schleswig-Holstein there is a 30 km hydrogen pipeline between Heide and Brunsbüttel. [114]

To facilitate the transport of huge amounts of green hydrogen, several new or repurposed hydrogen pipelines, interconnected in a European network, are under consideration for extension or reconversion[7] in the coming years. This section provides an overview of present knowledge and information on the offshore pipeline transport from Scotland to Germany, the import opportunities to landfalls in Germany and the onshore pipeline transport in Germany with focus on the hydrogen core network.

#### a) Offshore transport

For large volumes, offshore hydrogen pipelines, similar to natural gas pipelines, are an option for hydrogen supply between North Sea countries. In addition to the possibility of a Scottish hydrogen backbone link between Scotland and Germany presented in this study (see Hydrogen Supply from Scotland, above), other plans for offshore pipelines in the North Sea have been announced.

On the German side of the North Sea, the offshore hydrogen pipeline “AquaDuctus” is planned with funding announced and plans underway. This pipeline is planned to be more than 400 km long from landfall to the frontier of the German Exclusive economic zone (EEZ). Its transport capacity shall amount to 20 GW with a planned start of operation in 2030. It could import green hydrogen from different countries around the North Sea, as it could be an open access pipeline with a node to other European offshore pipelines. The first part of “AquaDuctus” (200 km) will connect the “SEN-1” area located in German EEZ and has been notified as IPCEI project. In the second phase, it will be extended to the edge of the German EEZ (a further 200 km). According to Gascade, [55] it would be possible to develop the first and second project phase jointly so they can both be realised by 2030, if there is the need. While the first connection between SEN-1 and Wilhelmshaven facilitates delivering offshore hydrogen to onshore hydrogen distribution networks (pipelines or mobile transport) and end-users, the extension would enable linkages to other offshore hydrogen pipelines, e.g. Norway, UK, Denmark, the Netherlands and Belgium. [55, 56]

#### b) Import infrastructure

There are several locations along the German North Sea coast that either already have an established natural gas pipeline landing point or could potentially be future hydrogen landing points, due to their location and facilities.

As shown in Figure 19 the current natural gas pipelines in the North Sea with landing points in Germany are:

- Europipe I (route: Draupner platform to Dornum, capacity: 45.7 $MSm^3/d$)
- Europipe II (route: Kårstø to Dornum, capacity: 71.2 $MSm^3/d$)
- Norpipe (route: Ekofisk to Emden, capacity: 44.4 $MSm^3/d$) [57]

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[7] e. g. under investigation for the Norway-Germany-Pipeline

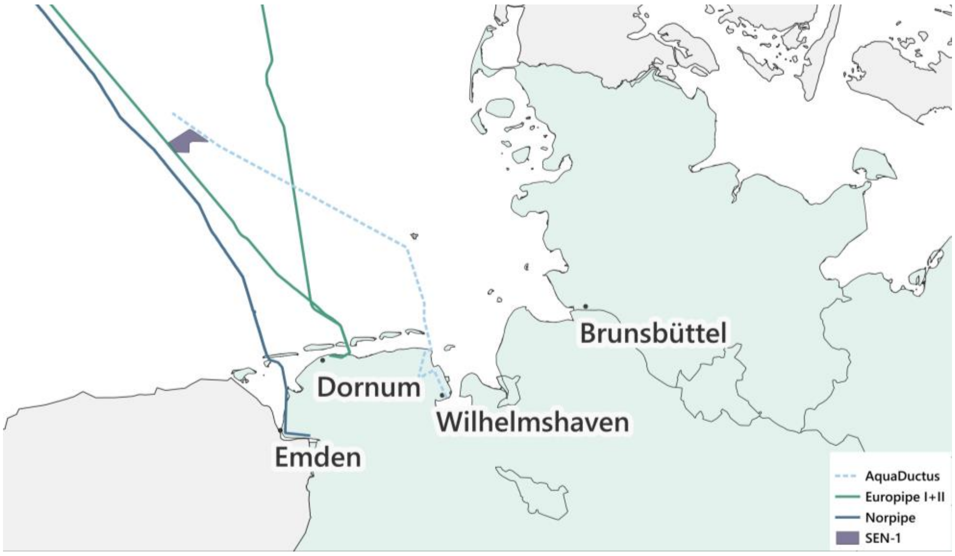

Figure 19: Current natural gas pipelines and planned AquaDuctus pipeline[8] to Germany in the North Sea. [53, 57]

In January 2023, Germany and Norway[9] agreed on a strategic energy partnership, focused on the supply of hydrogen from Norway to Germany. A direct hydrogen pipeline to be operational by 2030 is key to this. [76]

A feasibility study conducted by the German Energy Agency (dena) evaluated two concepts of a future hydrogen pipeline:

- Europipe's conversion to hydrogen with landfall in Dornum with a new receiving terminal close to the Europipe's one
- Construction of a new pipeline from Norway to Wilhelmshaven [35]

Within the feasibility study, four receiving locations were assessed in regards to their interface function to the German onshore hydrogen network: Wilhelmshaven and Brunsbüttel as potential new locations and Emden and Dornum as existing ones. The result showed that the Network Development Planning (NDP) for 2022-2032 would only need minor modifications for Wilhelmshaven, Emden and Dornum, whereas for Brunsbüttel modifications would lead to higher investment costs in comparison to the other. [35]

Furthermore, the German AquaDuctus project, which could also be a wider international cooperation project, is in dialogue with Norway. [55]

Alongside Wilhelmshaven, for the federal state of Lower Saxony, Emden could also be a plausible option for the Norwegian-German pipeline. [86]

So far, no announcements have been made by governments on how the hydrogen pipeline between Norway and Germany will be realised, though feasibility studies have been undertaken and this is being actively considered by the Germany Norwegian hydrogen task force.

Regarding the announced planning status of the hydrogen core network (see Figure 20), Wilhelmshaven is anticipated to be the landfall point for the AquaDuctus offshore hydrogen pipeline with expected commissioning by 2030, and an alternative landfall point in Büsum area is being considered. The AquaDuctus project itself states Wilhelmshaven as the landfall point in analogy to the hydrogen core network planning status. [4, 52, 53, 117]

### c) Onshore transport: Hydrogen network

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[8] based on planning status of hydrogen core network of 15th November 2023 (see chapter 3.1)

[9] Federal Economics Minister Robert Habeck and Norway's Prime Minister Jonas Gahr Støre

The ramp-up of the German **hydrogen network** is planned to be realised in two stages. Firstly, building up a hydrogen core network and secondly, further developing the hydrogen network on a regular basis, called network development planning (NDP) for gas and hydrogen. [36]

Hydrogen pipelines based on converted existing pipelines have reached a TRL of 8. To repurpose pipelines, the material compatibility must be evaluated on a case-by-case basis. However, according to European studies in particular, a large number of pipelines could be converted. During conversion, individual components that are not suitable for use in hydrogen networks would be replaced. There already exist several established solutions of replacement components. In addition, technical feasibility has already been demonstrated, e.g. in a project in the Netherlands, so that future networks would focus on this option in their planning. Overall, this option is more cost-efficient than a new built pipeline. [70, 74, 85].

New built pipelines already have reached a TRL 9.[10] The conversion of existing pipelines takes three to five years, while permitting and construction of new pipelines requires eight to ten years. [1]

### i. Hydrogen core network to connect large supply and demand centres

Function and legal process

The hydrogen core network shall form the basic framework to connect major hydrogen production and consumption sites at a supra-regional transport level, i.e. to link industrial hubs, storage facilities, power stations and import routes. [36, 123]

In December 2023, the Energy Industry Act (§28r EnWG) was amended to establish the legal framework and basis for the development of the hydrogen core network. [36]

The transmission system operators (TSOs) have modelled the hydrogen core network on the basis of a defined scenario framework. This scenario framework is based on a market enquiry, analyses of hydrogen strategies of the federal states and feedback on specific projects[11]. [36]

On 15th November, 2023, the TSOs submitted an informal draft application for the modelled hydrogen core network to the Federal Network Agency (BNetzA) and the BMWK. This is currently known as "**planning status of the hydrogen core network**". [36]

The BNetzA publicly consulted on this **planning status** until the beginning of January 2024. The results will now be used to further optimise modelling the hydrogen core network by the TSOs. A formal application must be submitted to the BNetzA by May 2024 at the latest. [36]

After a final consultation of the BNetzA, the **approval of the hydrogen core network is expected for summer 2024.** [36]

Planning status of 15th November 2023

According to the informal draft application (incl. planning status of the hydrogen core network), the network shall consist of around 9,700 km with a feed-in capacity of around 100 GW and a feed-out capacity of 87 GW. With 60 % converted natural gas pipelines and 40 % new built pipelines, the core network routes shall enable the connection of most relevant projects within Germany. The following project types are considered first in the hydrogen core network:

- IPCEI-projects, PCI/PMI-projects as well as projects supporting the integration of the core network into a European hydrogen network,
- Real-world laboratories of the energy transition ("Reallabore der Energiewende"), hydrogen storage projects and large combined heat and power (CHP) generation plant sites with more than 100 MW electrical CHP capacity,
- Projects in hard-to-abate industry sectors, which depend highly on green hydrogen for their decarbonisation, such as iron and steel, chemicals, refineries, glass and ceramics,

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[10] Author [1] uses the TRL-scale of IEA [67] from 1 "Initial idea" – 11 "Proof of stability reached". For comparison purposes in this study, it is converted into the TRL-scale of European Commission 1 – 9 (cf. Appendix Table 18)

[11] 309 projects were considered [36].

- Electrolysis-projects realising the feed-in of hydrogen.[12] [53, 117, 123, 124]

Some converted pipelines are due to be commissioned in 2025. Other converted and new pipelines are anticipated to be built successively until 2032. The investment cost of the core network is estimated at €19.8 billion. [117, 123]

The core network planning status already considers a feed-out volume of 280 TWh by 2032, which is twice as high as the demand forecast of 95-130 TWh for 2030 in the National Hydrogen Strategy. Thus, it is dimensioned for higher hydrogen transport volumes and future market ramp up. More than 50% of the feed-out volume (~160 TWh) would be the forecasted demand for large CHP plants. [36, 123]

Figure 20 provides a geographical overview on the hydrogen core network based on its current planning status. It also demonstrates the share of feed-out volumes in different regions in Germany.

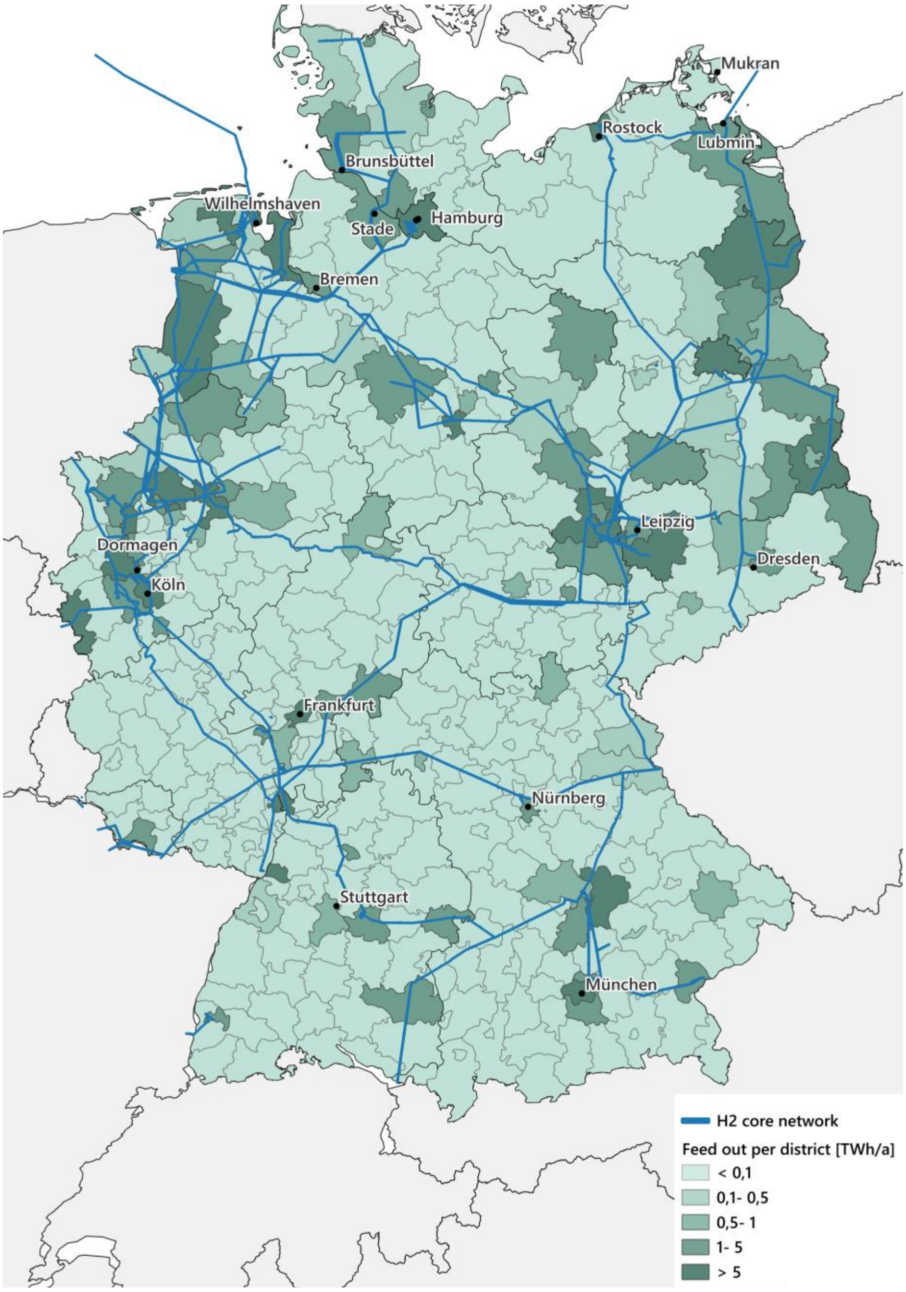

Figure 20: Overview of hydrogen core network based on planning status of 15th November, 2023. [123]

As outlined in section 2.1.2, Germany is projected to import around 50 - 70% of its hydrogen demand. For this reason, a German core network integrated into a European hydrogen network plays a particularly

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[12] Further sub-criteria based on project priority.

important role and also reflects the objectives of the National Hydrogen Strategy. Effective cooperation within the EU should make it possible to streamline market ramp-up, imports and the development of common standards. [123]

### ii. Integrated network development planning for gas and hydrogen for continuous optimisation and refinement on transmission system level

Function and legal process

In the second stage, further hydrogen network development is considered in the context of the integrated network development planning (NDP) for gas and hydrogen on a regular basis. The use of a scenario- and demand-based approach for the hydrogen network planning will support the development of a comprehensive, meshed network. The integrated planning process of gas and hydrogen should also enable the conversion of natural gas pipelines cost-efficiently and following a phased approach. [36]

The development of a legal basis for the second stage (draft law) has already been decided by the German Federal Cabinet. A further amendment to the EnWG is intended to make the following topics binding: the integrated network development planning for gas and hydrogen on a regular basis, the financing model for the core network and the regulated network access to the hydrogen networks. Once the parliamentary procedures have been completed, this amendment to the law is expected to come into force in mid-2024. [36]

First integrated network development plan (NDP) for gas and hydrogen

A first draft of a scenario framework for a future integrated NDP for gas and hydrogen will be created by 30th June, 2024, taking into account the interim report on the system development strategy, already published by BMWK. Based on these facts, a first draft of an integrated NDP for gas and hydrogen shall be developed by May, 2025 and shall be confirmed by regulatory authorities by June 2026. [36]

### iii. Development of hydrogen distribution networks and distribution system operators

Legal background

In comparison with the legal and planning development status of the hydrogen core network and NDP (at transport level), hydrogen distribution networks are mostly still in a very early planning stage.

In parallel to the development of the legal frameworks of the hydrogen core network and the integrated NDP, a new regulatory framework for hydrogen distribution networks is currently being developed. Therefore, a paper which will be published for consultation, is in preparation by BMWK. Furthermore, the “Hydrogen and decarbonised gas market package” passed by the European Union in December 2023, contains requirements for distribution networks and will impact the network design. [124]

Potential of hydrogen distribution networks

Distribution networks provide the potential to be directly connected to a huge amount of end-users. While today’s gas transmission networks supply only 500 industrial/commercial end-users with a feed-out-amount of around 189 TWh p. a., distribution networks supply 1.82 Mio. industrial/commercial end-users and 21.2 Mio. gas-supplied households – in total with an amount of 810 TWh p. a. [38]

A framework considering the transformation of distribution networks is emerging. Within the association “Deutscher Verein des Gas- und Wasserfaches” (DVGW) and in cooperation with the federation “Verband kommunaler Unternehmen” (VKU), the initiative "H2vorOrt" has been set up to develop the transformation of gas distribution networks towards climate neutrality by 2045. [59]

As part of this initiative, the “Gas network transformation plan” (GTP) has been developed as a bottom-up driven planning approach for the transformation of the gas distribution networks to climate neutrality. The GTP is a guideline that describes the standardised planning process from status quo towards a climate-neutral gas network in 2045. To this end, each DSO is developing a specific gas network transformation plan to convert its gas network. [50]

The approach is that these GTPs complete the picture of the hydrogen network developed by hydrogen core network and the integrative NDP with a bottom-up view provided by the GTPs provided by the DSOs. [50]

Blending hydrogen into existing pipelines

Blending hydrogen to existing gas network could be a way to partially decarbonise the gas supply and support the integration of decentral hydrogen production into existing energy system in the short-term. [116]

The technical feasibility of specific hydrogen blending proportions depends, among other things, on the fluctuation of the admixture proportion, the state of the gas network, or the end user's gas utilisation. The current planning basis of the transmission system operators (TSOs) is a maximum blending limit of 2 Vol.-%. Up to this proportion, it can be ensured that no investments are needed for network infrastructure adaptations or on consumer side. Although the TSOs consider higher admixture proportions to be possible in the future, they state that it would not be expedient to comprehensively and stepwise increase the proportion of hydrogen in transmission system as a constant mixing ratio could not be guaranteed due to changing gas flow directions on transmission system level, which would be challenging for accurate metering and consumers who require a homogeneous gas quality. [99]

Depending on local characteristics, gas distribution networks could handle blending up to 20 Vol.-%. [116] In a climate-neutral target network, different gas networks could exist in parallel: pure hydrogen networks, methane networks and blended gas networks. Blending in the distribution grid could accelerate the ramp-up of decentralised hydrogen production. [116]

### 3.1.2. Transporting hydrogen by mobile storage units

In order to transport gaseous hydrogen by mobile transport options, it must be compressed to a high-pressure level due to its low volumetric density. Typical pressure levels are 300, 380 or 500 bar.

To ensure ease of handling during transport, storage tanks are usually the size of normed containers (10 ft, 20 ft, 30 ft, 40 ft and 45 ft). The storage tanks can be designed either as a single large pressurised tank or as a series of horizontally or vertically bundled units. Normally, the tanks and bundled units are of a cylindrical shape. On trains, compressed gas tank wagons and multi-element gas containers (MEGC) are used. [30] Ships can be designed as container ships using the container-size storage tanks or as compressed gaseous hydrogen tanker with integrated storage tanks.

#### a) Offshore transport

Currently, single compressed hydrogen containers labelled as dangerous goods can be transported by sea-going vessels. They must be positioned on deck to ensure a sufficient ventilation in case of leakage. In future, when hydrogen imports take a more important role, and larger volumes need to be transported, other ship designs and safety concepts including certification and permitting need to be developed. Two designs at different development stages are shown in Table 6. They represent the two possible types of vessel for the transport of gaseous hydrogen: compressed hydrogen container carrier and tank vessels.

Table 6: Sea-going vessels for hydrogen transport

| **OffsH2ore** [77, 99] |
|---|
| • Design of a **container carrier** for compressed hydrogen for the transport of hydrogen produced in offshore-hydrogen-parks (500 MW) to offloading ports on shore.<br>• 500 bar, 400 t $H_2$/carrier<br>• Next development: aiming for Approval-in-Principle<br>• **Kongstein GmbH, PNE AG, SILICA Verfahrenstechnik GmbH, Fraunhofer ISE, Wystrach GmbH** |
| **H2Neo and H2Max** [69, 97] |
| • **Compressed hydrogen tanker**, approval in principle in 2021<br>• **250 bar, H2Neo: 26,000 $m^3$/tanker (430 t $H_2$), H2Max: 120,000 $m^3$/tanker (1200 t $H_2$)**<br>• Next development: H2Neo available from 2026, H2Max from 2030<br>• Provaris Energy Ltd |

### b) Import infrastructure

The required future import infrastructures for tank vessels and container carriers are different. According to our consultation of experts, container carriers could use common container terminals whereas tank vessels would need a dedicated infrastructure. They could either use a jetty that directly enables feed-in into a hydrogen pipeline or a filling station to enable further transport of mobile compressed hydrogen storage tanks. As with both vessel types, the required import infrastructure is still under development and not yet in operation. It therefore requires detailed development in terms of technology and safety.

### c) Onshore transport

As described in the introduction, the mobile transport options for hydrogen within Germany are trucks, trains and inland waterway vessels. A number of different storage units already exist, though more development can be expected. The project TransHyDE Mukran, supported by the Federal Ministry of Education and Research, is developing a 700 bar high-pressure spherical mobile storage tank. The corresponding transport infrastructure is also in place. A further increase in the volume of transported hydrogen may require an infrastructure newbuilt, such as an expansion of the railway network, loading stations and connections to demand sites. DB Cargo announced a capacity to supply 20 TWh of hydrogen by 2030. [30]

As with pipeline supply, the accessibility of demand sites to the distribution infrastructure limits the ability to supply by rail and inland waterway. Figure 21 shows the railway system and waterways in Germany.

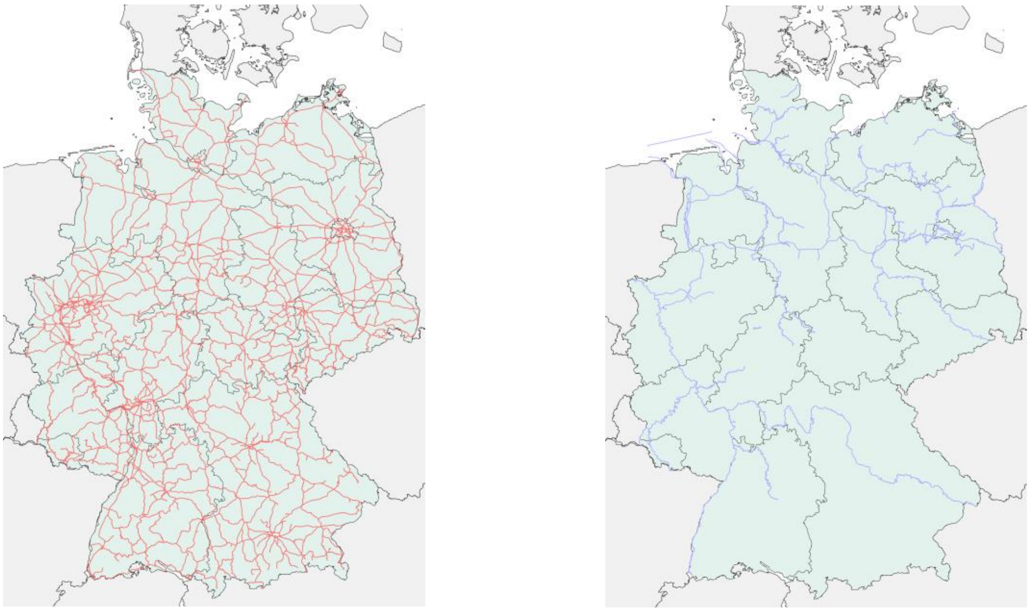

Figure 21: Railway system (left) and network of waterways (right) in Germany [12, 119]

A study on supply options of hydrogen demand sites in Germany was published by Fraunhofer IEG in January 2024. Firstly, demand sites in Germany were identified. Subsequently, investigation was undertaken as to whether the considered sites could be supplied with hydrogen by different transport infrastructures. It was shown that all the considered sites can be reached by the combination of train, vessel, and pipeline[13]. [108]

Based on the study results, onshore transport by mobile options is considered to be feasible once mobile containers for the transport of hydrogen and its derivatives are technologically developed. With the development of the hydrogen core network, and excluding consideration of supply to specific sites in this study, onshore pipeline supply of gaseous hydrogen is also considered to be generally feasible.

## 3.2. Liquid hydrogen

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[13] It was assumed that the sites could be supplied, if the pipeline, port or railway station was at most 20 km away.

As shown in chapter “Supply chain overview”, liquid hydrogen offers benefits such as high purity, low energy consumption during regasification and the opportunity of reusing the cryogenic energy released during this process. On the other hand, transporting liquid hydrogen is challenging due to the need to maintain its temperature at -253°C. While the onshore technology and transport options on land by truck and for rather short distances are very well developed, large $LH_2$ vessels and the corresponding import terminal development need to overcome some technological challenges, making import via the maritime route difficult to realise by 2030. [43, 95, 111, 120, 125]

### a) Offshore transport

The maritime international transportation of liquid hydrogen by tanker is in early development stages.

$LH_2$ vessels commercially operating overseas are not yet available. The first demonstration project of a $LH_2$ vessel is the “Suiso Frontier” operating between Australia and Japan. It has a capacity of 1,250 $m^3$ and was developed by Kawasaki Heavy Industries. Within this project, technical components such as tanks, pipeline infrastructures as well as arms for loading and unloading have been investigated in the exporting and importing port. [22, 43, 75, 90, 95]

To date, several project initiatives and industrial actors have emerged. Table 7 lists a small selection of the 16 $LH_2$-carrying tankers currently under development overall. [47]

Table 7: Announced industry-scale projects $LH_2$ [5, 9, 95]

| Company | Capacity | Timeframe |
|---|---|---|
| Korea Shipbuilding & Marine Engineering[14] | 20,000 $m^3$ | 2027[15] |
| Naval architect C-Job in partnership with LH2 Europe[16] | 37,500 $m^3$ | 2027 |
| Kawasaki Industries | 160,000 $m^3$ | Latter half of the 2020s |

Furthermore, there are ongoing research projects on $LH_2$ transport via ships. Some examples are listed in Table 8.

Table 8: Funding projects $LH_2$ [24, 44]

| Project name | Timeframe | Funding body | Focus |
|---|---|---|---|
| LH2CRAFT: Safe and Efficient Marine Transportation of Liquid Hydrogen | 06/2023 - 05/2027 | European commission; Clean Hydrogen Partnership | “Develop next generation, sustainable, commercially attractive, and safe long-term storage and long-distance transportation of Liquid Hydrogen ($LH_2$) for commercial vessels […].” [24]<br>It aims at developing high-capacity storages, e. g. 200,000 $m^3$, in the future. |
| HyShip | 01/2021 – 12/2025 | European commission; Clean Hydrogen Partnership | “[…] build a cargo vessel for commercial operation running on liquid hydrogen, establish a viable liquid hydrogen supply chain and a bunkering platform.” [44] |

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[14] Holding company for the shipbuilding branch of Hyundai Heavy Industries Group.
[15] Commercial operation is expected by Hyundai Industries in the decade after 2030 [111].
[16] Aims to build up a complete liquid-hydrogen supply chain in Europe by 2027.

Based on literature review, in general, $LH_2$ transportation technology via ships is still in prototyping stages, which implies the need for substantial investment for further development. The status of project announcements and the technical challenges to overcome indicate that it would be difficult to realise large-scale liquid hydrogen imports via the maritime route by 2030. [111, 120]

### b) Import terminal infrastructure

Incoming $LH_2$ vessels are docked at import terminals, where the $LH_2$ will be unloaded. Terminals can either be newly constructed[17] or converted from existing facilities. The liquid hydrogen then either undergoes regasification and is fed into the $H_2$ pipeline network or is directly transported to end-users. [43, 115]

The process of loading and unloading a $LH_2$ vessel is similar to that of LNG terminals with the difference that all components transferring $LH_2$ need to be equipped with special vacuum insulations. A jetty line with a length up to 1 km facilitates carrying liquid hydrogen from the vessel to the land side. Additionally, future liquid hydrogen terminals, analogous with LNG terminals, could provide the important functionality of "peak shaving". "Peak shaving" enables quickly balancing varying gas volumes required by consumers during a day, thereby ensuring $H_2$ grid stability. [125]

According to our conducted expert interviews and IRENA (2022), the $LH_2$ import terminal infrastructure has also reached the TRL 6 – 8. [47, 74] However, in Germany, terminal projects dedicated to $LH_2$ have yet to be announced. Within the German flagship project "TransHyDE" funded by the Federal Ministry of Education and Research (BMBF), the joint project "LNG2Hydrogen" is developing a scientific database and recommendations on how to realise future-orientated LNG terminals as hubs for hydrogen and its derivates. This comprehensive investigation encompasses various H2 transport vectors and involves developing import terminal concepts, standardisation, and addressing legal and regulatory aspects. [14, 27]

In general, in line with this project, the LNG Acceleration Act (cf. Overview of regulatory framework) addresses $H_2$-readiness of new LNG terminals. It remains to be seen to what extent the investigation will derive requirements specifically for $LH_2$ and whether completely new $LH_2$ terminals are needed or whether LNG terminals can be used.

### d) Onshore transport

After importing $LH_2$, the onshore transport of $LH_2$ can be realised via two paths – first, the transport of $LH_2$ to the end-user or second, the regasification of $LH_2$ into $GH_2$ with a feed-in into a pipeline.

#### i. Transportation of $LH_2$ to the end-user in mobile storage units

Liquid hydrogen transport by road within Germany is already established. In future, existing rail and waterway routes will also be able to be used to transport $LH_2$[18]. [125]

While road transport is feasible for short and medium-distance national and international routes, rail transportation focuses on long-distance international routes. [6]

For road transport, the tank of a trailer could be between 30 and 60 m³, holding between 2,100 and 4,200 kg of liquid hydrogen. An $LH_2$ trailer with a total weight of 40 tons can transport 3,370 kg. As it is a mature storage option, it is a safe transportation type. Distances between 300 and 400 km are considered as most economical. Currently, hydrogen refuelling stations are supplied in this way. The technology has reached TRL 9. [6, 47, 115]

For rail transport, containers have a volume of 115 m³, which could hold around 8,000 kg. For $LH_2$ transport, specialised cryo-containers are needed. These have not been approved yet. DB Cargo, for example, is involved in the development of innovative hydrogen containers and is testing the distribution logistics of pure hydrogen. For DB, hydrogen transportation via railway works for small-scale distribution

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[17] e. g. $LH_2$ demonstration project HySTRA has built a new $LH_2$ import terminal infrastructure in the port of Kobe, Japan. It provides a $LH_2$ tank capacity of 2,500m³ (150 t $LH_2$) and a loading facility [8].

[18] For details (cf. section 1)

of pure hydrogen to decentralised customers and end-users. Taking into account information from studies, the TRL could be assumed to be between 6 and 8[19]. [6, 32, 115]

### ii. $LH_2$ regasification and feed-in into a pipeline

According to IRENA “The reconversion (regasification) process is relatively simple and should not pose major limitations on its use for global hydrogen trade.” [74] The regasification process begins by heating up the $LH_2$ using either seawater[20] or air. However, during this process the energy previously used for the liquefication of the $GH_2$ is lost if there is no use of the cold, undermining the advantages associated with importing $LH_2$. [74]

At a small scale, regasification technology is mature, reaching TRL 9, and reaching at a large scale TRL 7. [74]

## 3.3. Ammonia

Ammonia can be used as a hydrogen carrier or as a feedstock, as it is the case today. It is transported liquefied at -33 °C, at ambient pressure or, much less commonly, at 20 °C and 9 bar. Therefore, the transport and storage technology is fully developed and available (TRL= 9) (see Chapter Supply chain overview). The technological bottleneck for using ammonia as a hydrogen carrier is the development of reactors for ammonia cracking to release hydrogen.

Ammonia import infrastructure is currently planned in Germany with a total capacity of 7.4 Mt $NH_3$ by 2030 and 9.1 Mt in the 2030s. The supplied ammonia can either be directly used as a fuel or chemical stock or be cracked back into hydrogen. If part of the ammonia were to be cracked back to hydrogen, several large-scale crackers would be needed. Three terminals are planning cracking with a total annual capacity of 3.47 Mt/a of $NH_3$, releasing 18 TWh/a $H_2$ by 2030. In the 2030s the cracking capacity is anticipated eventually to grow to 0.82 Mt/a $NH_3$, equivalent to 26 TWh. The remaining $NH_3$ will be distributed as feedstock.[21] It is noteworthy that direct ammonia use is preferable in terms of efficiency.

### Offshore transport

The transport by ship is usually carried out in fully refrigerated non-pressurised tankers of different capacities:

- LPG tanker: approximately 40,000 t $NH_3$ (approx. 58,800 $m^3$ $NH_3$)
- Gas carrier / large gas carrier (LGC): 30,000 – 80,000 $m^3$ $NH_3$
- Very large gas carrier (VLGC): more than 80,000 $m^3$ $NH_3$

Currently, there are 200 vessels in operation capable of transporting ammonia, with global annual transportation reaching 20 Mt. In the coming years, the demand for ammonia gas tankers will increase significantly with the introduction of hydrogen and the expected volume of green ammonia to be transported. Currently, there are 200 vessels in operation capable of transporting ammonia, with global annual transportation reaching 20 Mt. In the coming years, the demand for ammonia gas tankers will increase significantly with the introduction of hydrogen and the expected volume of green ammonia to be transported. [72, 98]

### Import terminal

In Germany, plans are underway to construct, expand or adapt green ammonia import terminals, reaching a capacity of 7.4 Mt ammonia until 2030, eventually increasing to 9.1 Mt. Details of these projects are outlined in Table 9, with Figure 22 illustrating the anticipated ramp up in import capacity of green ammonia. As the LNG Acceleration Act requires the conversion of land-based LNG terminals to ammonia by 2044 at the latest, more ammonia import capacity could be available if the terminals are not converted

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[19] own assumption based on information derived from literature review
[20] Done by 95% of LNG facilities [74].
[21] The projects may change capacities to adapt to market conditions.

to other energy sources (see Overview of regulatory framework). It has been announced that the land-based LNG terminal in Stade will be ready for ammonia. Its LNG capacity of 13.3 bcm is equivalent to 9.7 billion tonnes of ammonia.[22] [81]

Three of the announced projects focus on the cracking of ammonia to hydrogen. Cracking units with a capacity of 1 to 1,500 kg $H_2$/d are currently used in the metal processing industry (TRL= 8 - 9). [108] In contrast, cracking processes for the large-scale conversion of ammonia are still in the testing phase (TRL= 5 - 6). [110] In the Mabanaft and Air Products terminal, more than one cracker is installed to achieve the desired cracking capacity. [82]

The import terminals in Brunsbüttel (RWE), Wilhelmshaven (Uniper) and Hamburg (Mabanaft & Air Products) intend to supply both hydrogen, and ammonia. As the market for green hydrogen and ammonia is still developing and uncertain, it is possible that the volumes of cracked and distributed ammonia will be adjusted and differ from the volumes stated in the press releases. Yara announced that it will expand the capacity of its ammonia terminal in Rostock and adapt its export terminal in Brunsbüttel for import purposes in order to be ready for possible import volumes in 2023. [127]

In addition to the land-based terminals, there is an industrial development project by LNG Höegh to install ammonia crackers on floating import terminals. This floating terminals could complement the land-based terminals and offer more capacities for hydrogen import countries like Germany. [61]

Table 9: Announced ammonia import terminals in German sea ports

| Start | Location | Partner | Transport | Source |
|---|---|---|---|---|
| **2023** | Rostock & Brunsbüttel | YARA GmbH & Co. KG | Rostock: cooperation with VNG for trade and distribution<br>Brunsbüttel: no detailed information | [118, 127] |
| **2026** | Brunsbüttel | RWE AG | ammonia transport by train, cracking unit will be set up after 2030 | [80, 100, 121] |
| **2027** | Hamburg | Air Products GmbH, Mabanaft GmbH & Co. KG | ammonia cracking (hydrogen supply) and ammonia supply | [82, 91] |
| **2030** | Wilhelmshaven | Uniper Hydrogen GmbH | ammonia cracking and $H_2$ feed in pipeline and ammonia transport by train | [28] |
| **2028** | Wilhelmshaven | BP Europa SE | ammonia cracking and $H_2$ feed in pipeline | [11] |

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[22] Ammonia density 0,69 kg/l at -33 °C

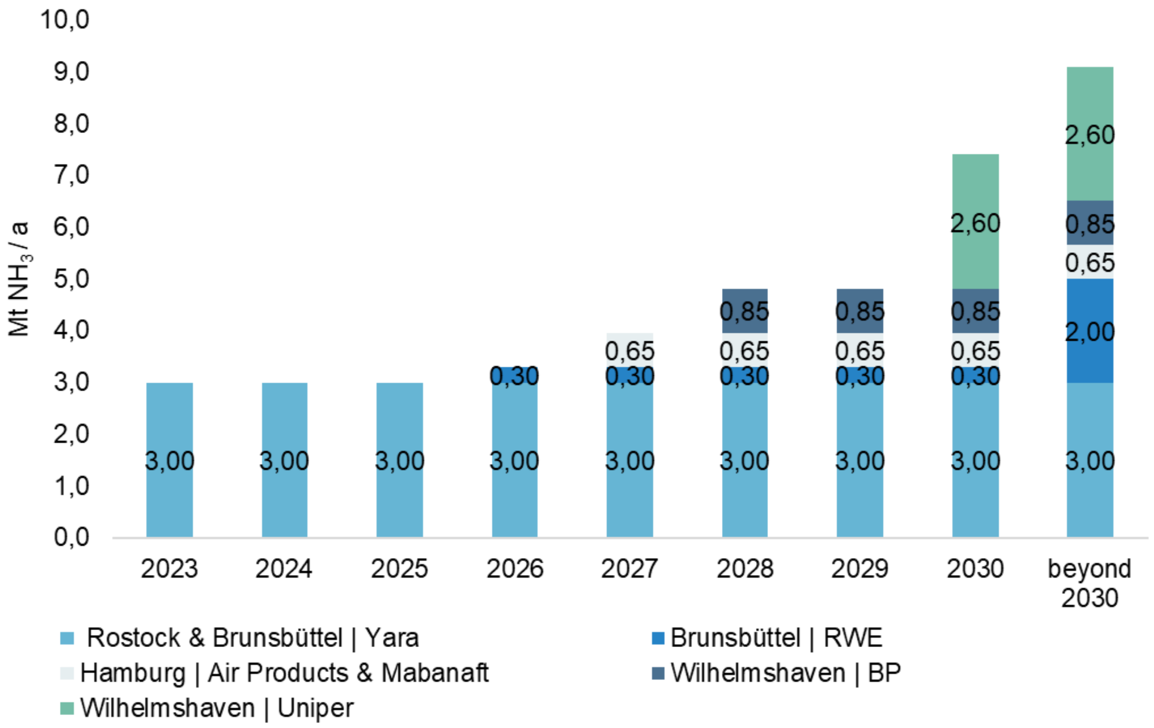

Figure 22: Capacity of announced ammonia import terminals (cf. Table 7) [11, 28, 80, 82, 91, 92, 100, 127]

### Onshore transport

In Germany, the primary mode of transporting ammonia currently is by rail. Nevertheless it can also be transported by truck and inland vessel. Ammonia pipelines exist only at industrial sites.

In order to increase the supply capacity for future markets, the infrastructure (stations, transhipment points, site connections) and routes may have to be adapted or new ones built. [96, 107, 108]

In the case of ammonia cracking, the released hydrogen is planned to be fed into the hydrogen pipelines connected to the terminals.

## 3.4. Synthetic natural gas transport

To transport natural gas without a pipeline connection, it is converted into liquefied natural gas (LNG) by cooling it to temperatures between -161 °C and -167 °C. As with liquid hydrogen, the energy density is higher than if it were transported in compressed form. SNG is equivalent in chemical properties to conventional liquified natural gas, which is primarily composed of methane (approximately 98 %). Therefore, from the technical perspective the same infrastructure as for LNG can be used (TRL = 9). [39] Today, four land-based stationary LNG terminals and five floating terminals are planned in Germany with a total capacity of 54.3 bcm LNG. [18, 81, 92]

### Offshore transport

Table 10 shows the capacities of LNG carriers, which can also be used for SNG. As of 2022, there were a total of 734 LNG carriers operating worldwide. [109]

Table 10: Capacities of SNG carriers [128]

| Vessel | Capacity in m³ SNG | GWh SNG [23] |
|---|---|---|
| **LNG carrier (average)** | 120,000 – 145,000 m³ | 1,39 – 1,68 |

---

[23] lower heating value 11,6 kWh/$m^3$ [39].

| | | |
|---|---|---|
| **LNG carrier (largest)** | 266,000 m³ | 3,09 |

**Import terminals**

Following the Russia-Ukraine war, Germany enacted the LNG Acceleration Act to fortify future energy security. This legislation aims to accelerate the construction and commissioning of the LNG terminals (see Overview of regulatory framework). The LNG terminals are equipped with regasification units to feed the natural gas into the pipeline network. [18] Figure 23 illustrates the development of terminal capacities, comprising both land-based and floating regasification and storing units (FRSU).

The LNG Acceleration Act requires land-based terminals to be converted to green hydrogen facilities by 2044 at the latest. In addition to ammonia, other green energy sources are possible, such as SNG. If the SNG is planned to be converted to hydrogen at the terminal, the processes are steam reforming (TRL = 9) or pyrolysis (TRL= 4). In that case, the terminal would need a carbon management strategy including carbon capture and storage or transport and use measures (cf. Overview of regulatory framework). The carbon capture technology for hydrogen production from methane have been demonstrated at scale and are in the early adaption phase (TRL= 8). [71][24]

Following the final investment decision, the construction of the land-based LNG terminal in Stade will begin. It has been announced that in addition to LNG, SNG and biomethane will also be imported. Moreover, the terminal will be built to be ammonia ready, for example the foundation will be designed to carry the extra weight of ammonia. [81]

The Tree Energy Solutions (TES) terminal in Wilhelmshaven plans to import 1 TWh/a SNG from 2027 with further increasing volumes thereafter. Depending on the demand a certain amount of the methane can be converted to hydrogen to feed into the hydrogen core network. [112]

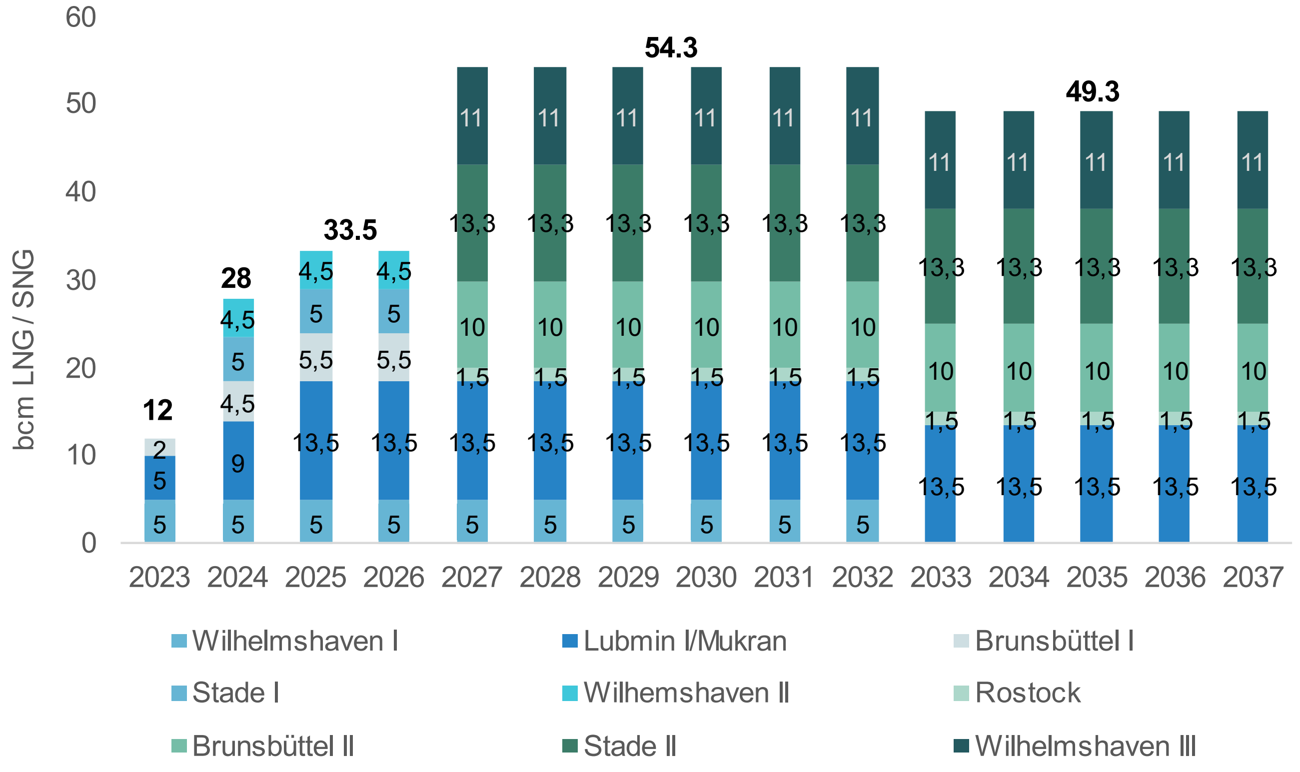

Figure 23: LNG terminal capacities in Germany. Blue coloured sites are FRSU, green ones land-based LNG terminals [18, 81, 92]

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[24] The TRLs from the report of the IEA are adapted to the definition used in this report, IEA's TRL = 8 – 9. [46, 71]

**Onshore transport**

Within Germany, methane can be transported via the natural gas network, a 550,000 km long distribution network and a 40,000 km transmission network. [122]

For smaller units a transport by truck or train is possible. LNG trains can carry approximately 14,550 MWh. [107]

### 3.5. LOHC

Unlike the other $H_2$-transport vectors, Liquid Organic Hydrogen Carriers (LOHC) can only be used as a hydrogen carrier and not as feedstock material for direct use. In hydrogenation units (TRL= 5 - 7) and dehydrogenation units (TRL= 5 - 7) the carrier absorbs and releases $H_2$ through chemical reactions. ([110] and expert interview)

LOHC can be transported using the existing infrastructure for refined products and crude oil. Therefore, transport infrastructure suitable for LOHC is readily available and the technology is mature for mobile supply options (TRL= 9). The technological bottleneck for establishing a LOHC supply chain is the development of reactors for hydrogenation and dehydrogenation. Today, there are no plans for a LOHC dehydrogenation infrastructure in German Sea Ports, but for Amsterdam and Rotterdam with a capacity of around 41,000 t $H_2$ per year.

**Offshore transport**

For transporting LOHC in vessels, crude oil and refined product tankers can be used. The global fleet has various types with a range of capacities from 10,000 DWT to 550,000 DWT[25]. Table 11 shows the hydrogen capacities of some types. [60]

Table 11: Capacities of crude oil and refined product carriers to transport LOHC [60]

| Transport option | Capacity in t LOHC | Capacity in t $H_2$ [26] |
|---|---|---|
| General Purpose | 10,000 – 25,000 | 620 – 1,550 |
| Long range 1-type tanker | 45,000 – 80,000 | 2,790 – 4,960 |
| Long-range-2 type tanker | 80,000 – 160,000 | 4,960 – 9,920 |
| Very large crude carrier (VLCC) | 160,000 – 320,000 | 9,920 – 19,840 |

**Import terminal infrastructure**

For importing hydrogen stored in LOHC, two options are available. Option one involves transferring the LOHC similar to conventional oil and refined products from ports to the demand sites, where a dehydrogenation unit is installed. The second option entails establishing a large-scale dehydrogenation unit (import terminal) at a Sea Port, where the hydrogen is released and distributed to demand centres e.g. via pipelines.

Currently, no LOHC import terminals in German Sea Ports have been announced, but such projects are planned in the Netherlands in Amsterdam and Rotterdam with release plants with total capacities of 36,000 t $H_2$/a and 4,975 t $H_2$/a by 2030. From these locations, onshore supply chains to German locations

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[25] DWT = deadweight tonnage, measures the weight a vessel can carry

[26] gravimetric energy density = 62 kg $H_2$/t LOHC

are planned. [62, 65] Table 12 summarises LOHC projects in Germany, taking into account the entire supply chain between production and demand locations.

Table 12: Announced LOHC projects in Germany

| **Project** | **Locations** | **Project partner** | **Handling capacity** |
|---|---|---|---|
| LOHC handling terminal (Project part of the IPCEI Hy2Infra workstreams) | Rotterdam | Vopark | Release plant: 4,300 t $H_2$/year [45] |
| Hector<br>(2025) | Dormagen, Rotterdam | Hydrogenious, Vopark | (Storage plant in Dormagen, Germany and release plant with 657 t $H_2$/year in Rotterdam) [62, 65] |
| H2A-RP<br>(before 2030) | Amsterdam | Hydrogenious | 36,000 t $H_2$/year [65] |
| Green Hydrogen@Blue Danube<br>(Project part of the IPCEI Hy2Infra workstreams) | From Austria and south Europe along the river Danube to a release plant in Bavaria (southern Germany) | Hydrogenious, Verbund AG, Bayernoil, Bosch, MAN Energy Solutions, Clariant | Release plant: 1,000 – 2,000 t $H_2$/year [66, 101] |

## Onshore transport

If the dehydrogenation unit is located at the demand site, three options exist for the inland transport of LOHC: truck, train, and barge (see Table 13).

Trucks are suitable for small quantities over short distances while trains and barges are suitable for medium quantities over medium distances.

In the case of dehydration at the port, the released gaseous hydrogen can be transported using the options outlined in section 3.1.

Table 13: Transport capacities of mobile transport options for LOHC [2, 64]

| **Transport option** | **Capacity in LOHC** | **Capacity in t $H_2$** [27] |
|---|---|---|
| Tank container | 21 $m^3$, 25 $m^3$ | 1.13, 1.35 |
| Tank truck | 10 $m^3$, 30 $m^3$ | 0.54, 1.62 |
| Tanker (barge) | e. g. 2,300 t | 142.2 |
| Tanker lorry (train) | e. g. 2,296 t | 124 |

---

[27] gravimetric energy density = 62 kg $H_2$/t LOHC, volumetric energy density = 54 kg $H_2$/$m^3$ LOHC

# Supply chain assessment

With regard to the development of an import infrastructure between Scotland and Germany, the choice of a hydrogen derivative depends on a variety of factors both in the exporting and the importing country. To conduct a comprehensive supply chain assessment for hydrogen and its derivatives all steps were considered: production, onshore transport within Scotland, export terminals, offshore transport, import terminals, and onshore transport within Germany. The key facts from the previous chapters are listed in Table 14.

Table 14: Key facts of technological maturity of the supply chains of hydrogen and its derivatives

| **Gaseous hydrogen** |
|---|
| Production: Most hydrogen is currently produced in Scotland by SMR or ATR (TRL= 9), but electrolytic production is growing and is expected to play an increasingly important role in Scotland's hydrogen ambition as offshore wind developments become established. Green hydrogen sites for export in Scotland are expected to be clustered around offshore wind development areas.<br>Onshore transport: Currently, the transport of gaseous hydrogen in Scotland is performed by tanker trucks (TRL= 9). Existing pipeline infrastructure for hydrogen transport is limited in the UK, but a number of hydrogen transmission projects are under consideration. The development of transmission networks linking production sites to industrial clusters and terminals will involve the use of repurposed NTS pipelines where possible as well as the commissioning of new build pipelines (TRL= 7).<br>Export terminal: Scotland has an extensive network of offshore and coastal infrastructure, as well as associated supply-chains. The Sullom Voe, Flotta, Cromarty Firth and St Fergus terminals are well placed for the export of hydrogen. The inclusion of hydrogen export facilities can extend the economic lifetime of existing hydrocarbon terminals.<br>Offshore transport: Offshore pipelines stand out as the preferred option for transporting large quantities of gaseous hydrogen. $CGH_2$ carrier vessels are in development or demonstration (depending on the project). First vessels are expected in 2026/2027. The technology is less mature compared to the other carriers.<br>Import terminal and landfalls: Several potential landfalls for offshore hydrogen pipelines have been identified and evaluated. This facilitates the development of the $GH_2$ supply chain based on pipelines. Regarding the planning status of the hydrogen core network, it seems likely that AquaDuctus would be the offshore pipeline to Germany with a landfall in Wilhelmshaven. In the case of a hydrogen supply by offshore vessels, the described port infrastructure needs to be established.<br>Onshore transport: First pipelines of the hydrogen core network will be commissioned by 2025, with the core network expected to be finalised by 2032 (TRL = 8-9). Various mobile transport options for compressed hydrogen by truck, train or vessel are available (TRL= 9). |
| **Liquid hydrogen** |
| Production: Hydrogen liquefication is a well-established but energy intensive process. Currently, liquid hydrogen production is mostly aimed for use as fuel in the aviation sector and is not performed at large-scale.<br>Onshore transport: onshore transport can be performed by $LH_2$ truck (TRL 9) or train (TRL 6-8), but potential boil-off during delivery is a challenge. |

Export terminal: No plans for the development of export terminals for liquid hydrogen have been announced at present but as production capacity increases, the establishment of export terminals is likely towards the 2030s (TRL 6-8).

Offshore transport: different companies have successfully demonstrated $LH_2$-tanker options, with different companies announcing plans for various vessels before 2030 (cf. Table 7). Based on the conducted expert interview, the first large-scale commercially operational vessel is projected to be available by 2029 (TRL 6-8).

Import terminal: Currently, no German $LH_2$ import terminal project has been announced. Dynamics considering $LH_2$ demand can be perceived in aviation and mobility. Research also focuses on recovering cryogenic energy during regasification and the $H_2$ readiness of LNG terminals. It seems plausible that importing $LH_2$ via terminals would be possible by early 2030s (TRL 6-8).

Onshore transport: Onshore road transportation is already established (TRL 9) – rail is in development stages (TRL 6-8)[28]. Regasification (TRL 7-9) leads to transport by pipelines in gaseous form.

**Ammonia**

Production: The availability of renewable ammonia production facilities is limited although there are plans to enhance production capacity and develop supporting infrastructure. The Zero Carbon Humber initiative in England is aiming to install infrastructure for the use of hydrogen in a low carbon ammonia production plant by 2027.

Onshore transport: Well established train and truck transport, with networks likely to expand as demand grows and export options become available.

Export terminal: Currently there are no ammonia export terminals in Scotland, but existing terminals with LPG export capabilities are similarly equipped and expected to be able to accommodate ammonia handling, namely Sullom Voe and Grangemouth in Scotland and Easington in England.

Offshore transport: With a TRL = 9, ammonia is already handled as a feedstock material, transported liquefied in gas carriers.

Import terminals: Six ammonia import terminals are scheduled for development starting from 2026 (TRL = 9), three are equipped with cracking units to release the hydrogen to the hydrogen core network. Their capacity is 7.4 Mt of $NH_3$ until 2030, eventually increasing to 9.1 Mio. tonnes (cf. Table 9). Large-scale cracking units are still under development with a TRL of 5 – 6, while small-scale units have a TRL of 8 – 9. [108, 110]

Onshore transport: Onshore transport is possible by mobile transport options, with trains currently transporting the largest quantities (TRL = 9). However, it is likely that an extension of the rail network and handling station will be necessary to match the increasing quantities.

**Synthetic natural gas (liquified)**

Production: No large-scale production projects currently planned. The capture of $CO_2$ for feedstock and costs of production represent significant challenges (TRL = 6)

Onshore transport: Well established transport infrastructure, additional developments dependant on demand (TRL = 9).

Export terminal: Well established LNG export infrastructure (TRL = 9).

---

[28] Assumption. For details see chapter 3.2.

Offshore transport: The global fleet of LNG carriers and offshore natural gas pipelines in the North Sea have a TRL = 9. The existing LNG infrastructure can be repurposed for SNG, as SNG is equivalent in chemical properties to conventional liquified natural gas. [29]

Import terminal: Ramp up of LNG import terminal capacity is underway with the LNG acceleration act (TRL = 9). Carbon management strategy of the sites is needed in case reforming to $H_2$ becomes necessary. Today, nine floating terminals with a total capacity of 54.3 bcm LNG are planned in Germany. [15, 71, 79]

Onshore transport: At the import terminals, after passing through regasification units, the gaseous methane is fed into the natural gas pipeline network for distribution to consumers (TRL = 9). That would be possible for SNG as well. If the SNG is converted back to gaseous hydrogen, the gaseous hydrogen infrastructure described above would have to be used for onshore transport. In this case a carbon management measures would need to be implemented at the terminal.

**LOHC**

Production: Well established, but application is currently limited by the efficiency of the dehydrogenation processes. Co-location in industrial sites where waste heat can be reused for dehydrogenation would provide a cost benefit.

Onshore transport: Onshore transport requires similar infrastructure to existing petroleum products (TRL = 9).

Export terminal: There is potential for LOHC export at small- and large-scale from St Fergus and Sullom Voe terminals in Scotland. Handling implications aren’t significantly different from existing petroleum products (TRL = 9).

Offshore transport: LOHC is transported using the same infrastructure as oil and refined products, therefore existent units can be used (TRL = 9).

Import terminal: Lack of dehydrogenation projects at German seaports, existing project in Amsterdam and Rotterdam with capacities of 36,000 t $H_2$/a and 4,975 t $H_2$/a by 2030 (cf. Table 12). In western Germany, dehydrogenation plants with a total capacity of 1,000 to 2,000 t $H_2$/a are planned. In the LOHC supply chain, the dehydrogenation unit has the lowest TRL = 5-7.

Onshore transport: Similar to offshore transport, LOHC is transported using the same infrastructure as oil and refined products. Therefore existent units can be used (TRL = 9).

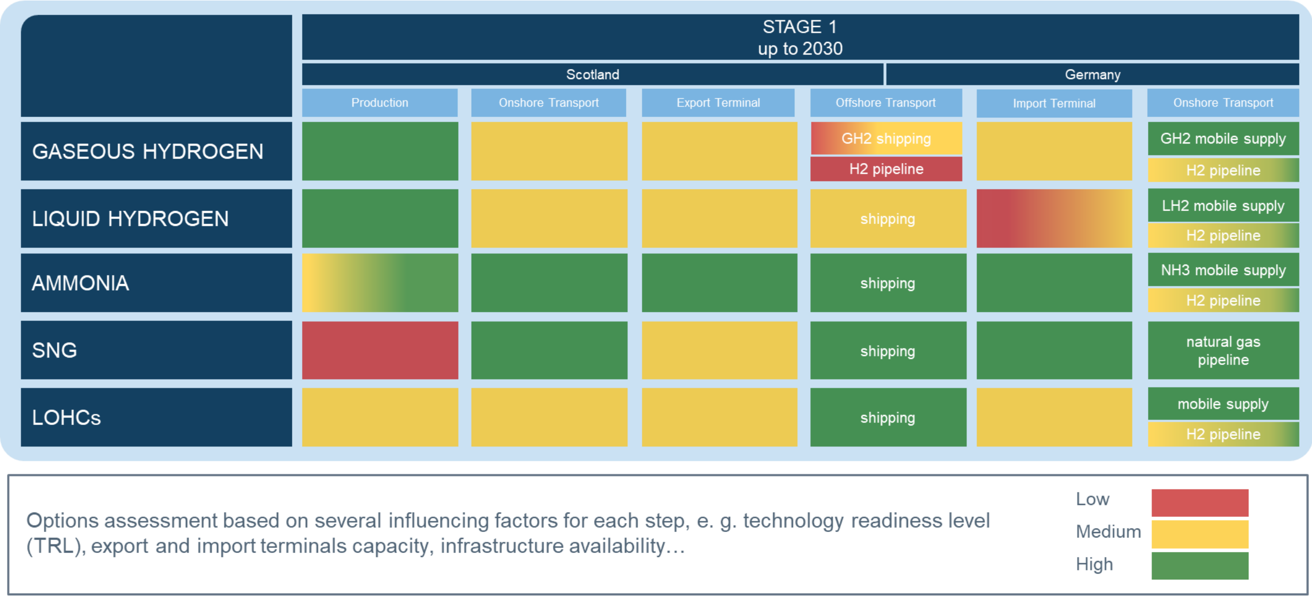
To evaluate the supply chains, for each step two main critical factors pivotal to the efficiency and viability of the supply chain were taken into consideration. Table 14 summarises the key aspects used for the evaluation. These are rated according the criteria listed in Table 15, employing a three-tiered traffic light system. A green rating signifies a positive assessment, while amber and red ratings indicate progressively less favourable evaluations.

Table 15: Evaluation criteria for all supply chain steps

| **Criteria** | |
|---|---|
| **Technology maturity** | Technology readiness level<br>(green: TRL= 8 – 9, yellow: TRL= 6 - 7, red: TRL< 6 |
| **Infrastructure availability** | existing infrastructure and planned projects<br>(green: large-scale, yellow: small-scall, red: no projects) |

The evaluation of the information accordance with the traffic light system results in the synthesis for the first stage up to 2030 shown in Figure 24. This gives an overview on the detailed information in Table 14 above. Currently, $GH_2$ carriers for offshore transport are undergoing development but are not considered an alternative to pipeline transport. Additionally, no $LH_2$ import terminals have been announced in Germany. The production of synthetic methane presents technical challenges primarily related to $CO_2$ capture and utilization and is not currently being produced in the UK.

Overall, ammonia emerges as the most feasible option for accelerating the establishment of hydrogen supply chains towards 2030, with its infrastructure and transportation capabilities already well-planned and progressing.



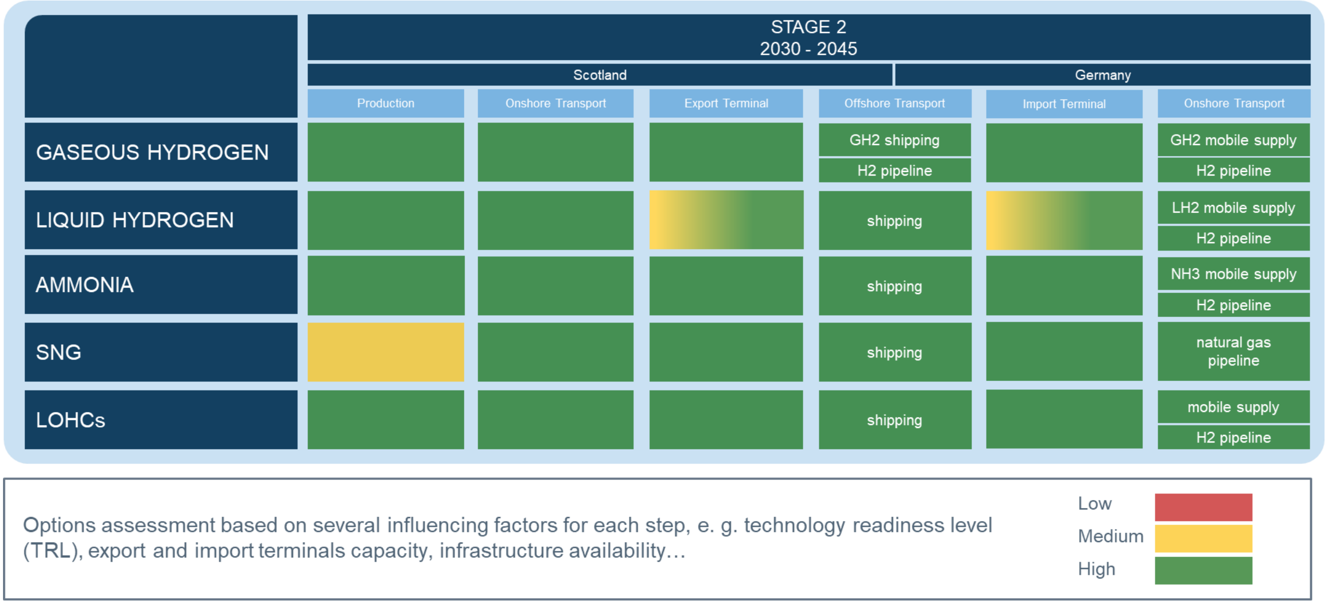
| | STAGE 1 up to 2030 | | | | | |
|---|---|---|---|---|---|---|
| | Scotland | | | | Germany | |
| | Production | Onshore Transport | Export Terminal | Offshore Transport | Import Terminal | Onshore Transport |
| GASEOUS HYDROGEN | 🟩 | 🟨 | 🟨 | 🟥🟨 GH2 shipping<br>🟥 H2 pipeline | 🟨 | 🟩 GH2 mobile supply<br>🟨🟩 H2 pipeline |
| LIQUID HYDROGEN | 🟩 | 🟨 | 🟨 | 🟨 shipping | 🟥🟨 | 🟩 LH2 mobile supply<br>🟨🟩 H2 pipeline |
| AMMONIA | 🟨🟩 | 🟩 | 🟩 | 🟩 shipping | 🟩 | 🟩 NH3 mobile supply<br>🟨🟩 H2 pipeline |
| SNG | 🟥 | 🟩 | 🟨 | 🟩 shipping | 🟩 | 🟩 natural gas pipeline |
| LOHCs | 🟨 | 🟨 | 🟨 | 🟩 shipping | 🟨 | 🟩 mobile supply<br>🟨🟩 H2 pipeline |

Options assessment based on several influencing factors for each step, e. g. technology readiness level (TRL), export and import terminals capacity, infrastructure availability…

Low 🟥
Medium 🟨
High 🟩

Figure 24: Evaluation of transport options until 2030

For the second stage, technological advancements and market growth are anticipated to pave the way for the comprehensive establishment of several hydrogen supply chains by 2045 (See Figure 25). This progress could see pipeline infrastructure supporting the transport of gaseous hydrogen, in parallel with further enhancements in ammonia utilisation, the potential for $LH_2$ import terminals to accommodate increasing demand, and the establishment of a mature infrastructure for Synthetic Natural Gas (SNG) and Liquid Organic Hydrogen Carriers (LOHCs). It is assumed that all technologies will mature in the second phase.



| | STAGE 2 2030 - 2045 | | | | | |
|---|---|---|---|---|---|---|
| | Scotland | | | | Germany | |
| | Production | Onshore Transport | Export Terminal | Offshore Transport | Import Terminal | Onshore Transport |
| GASEOUS HYDROGEN | 🟩 | 🟩 | 🟩 | 🟩 GH2 shipping<br>🟩 H2 pipeline | 🟩 | 🟩 GH2 mobile supply<br>🟩 H2 pipeline |
| LIQUID HYDROGEN | 🟩 | 🟩 | 🟨🟩 | 🟩 shipping | 🟨🟩 | 🟩 LH2 mobile supply<br>🟩 H2 pipeline |
| AMMONIA | 🟩 | 🟩 | 🟩 | 🟩 shipping | 🟩 | 🟩 NH3 mobile supply<br>🟩 H2 pipeline |
| SNG | 🟨 | 🟩 | 🟩 | 🟩 shipping | 🟩 | 🟩 natural gas pipeline |
| LOHCs | 🟩 | 🟩 | 🟩 | 🟩 shipping | 🟩 | 🟩 mobile supply<br>🟩 H2 pipeline |

Options assessment based on several influencing factors for each step, e. g. technology readiness level (TRL), export and import terminals capacity, infrastructure availability…

Low 🟥
Medium 🟨
High 🟩

Figure 25: Evaluation of transport options until 2045

As Figure 24 shows that ammonia offers a completely established supply chain for Stage 1, it is worth looking more closely at the potential match of export and import volumes of ammonia in Figure 26. Scotland indicates possible export volumes of up to 35 TWh of hydrogen annually, which would be equivalent to around 6 tonnes of ammonia.[29] An ammonia import infrastructure is currently planned in Germany with a total capacity of 7.4 Mt $NH_3$ by 2030, potentially reaching 9.1 Mt $NH_3$ after 2030. Assuming full availability for Scottish exports, the capacity of German $NH_3$ import terminals would be sufficient to import the totality of Scottish export volumes for Stage 1. Figure 27 shows the most likely export and import points in both countries for the distribution of ammonia through shipping.

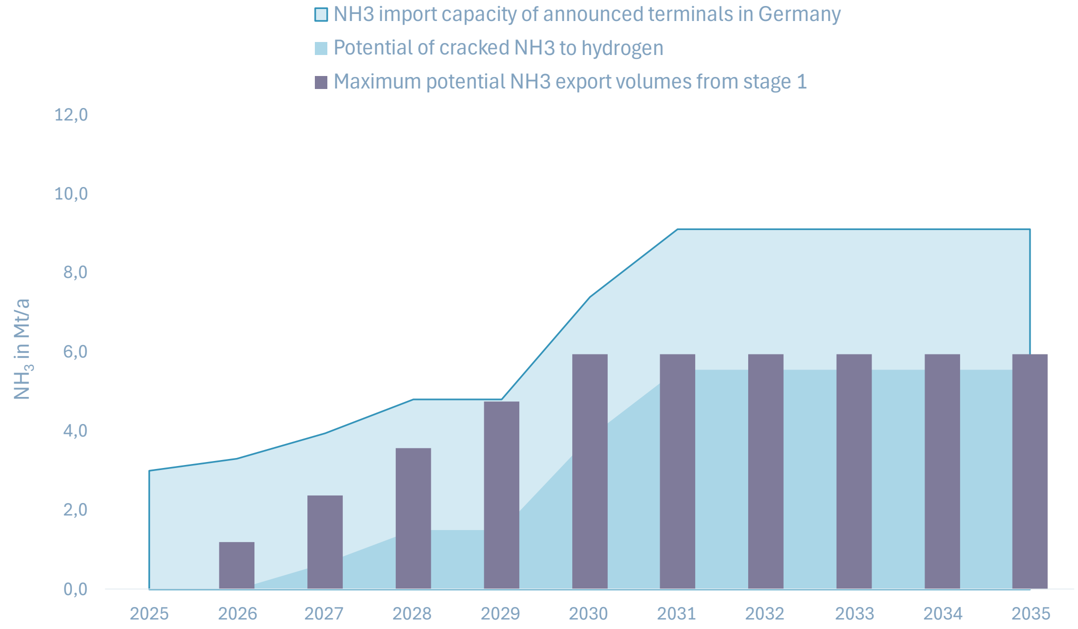


Figure 26: Ammonia pathway potential in Germany

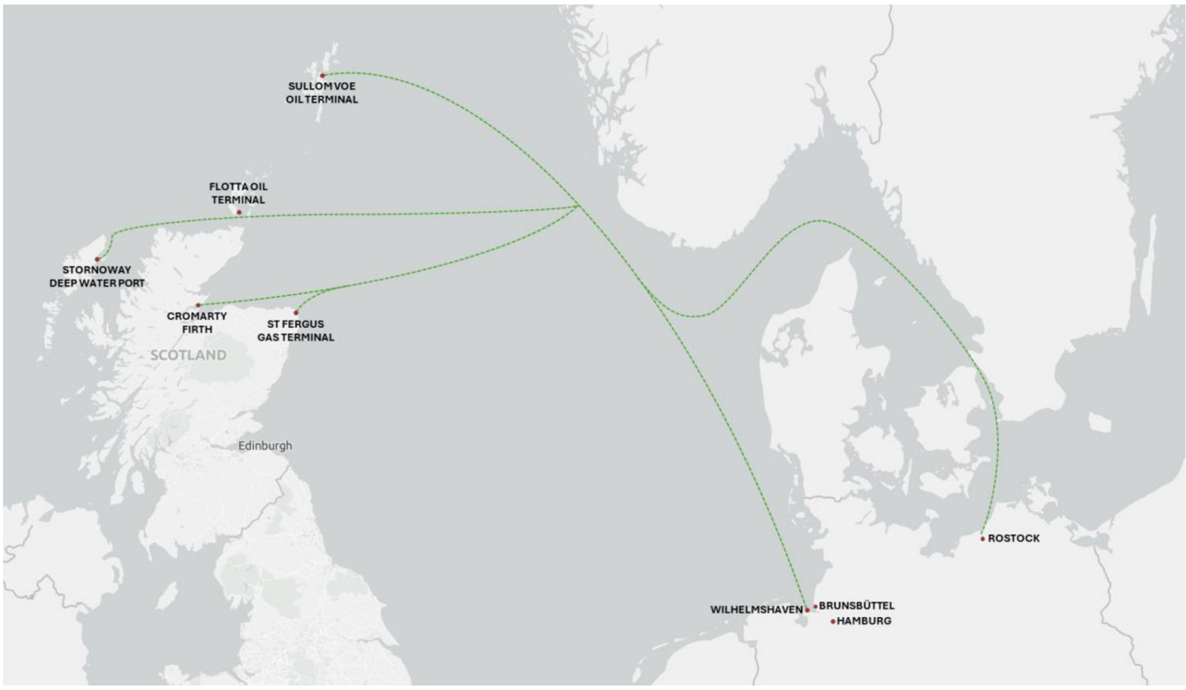


Figure 27: Potential export and import points for the distribution of ammonia by ship. [30]

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[29] Hydrogen has a mass fraction of 17.65% of ammonia.

[30] Routes presented are illustrative and do not accurately represent established shipping lanes.

# Matching scenarios between Scottish supply and German Demand

## 1. Framework conditions and assumptions

Based on the supply, demand and transport analysis presented in sections 2 and 3, it is evident that Germany could assimilate the full capacity of Scotland's green hydrogen supply. A fundamental analysis of the anticipated availability and technical maturity of five supply chains shows the preferred options for different time frames.

As a critical component of decarbonisation strategies, hydrogen production in Scotland is expected to develop at a fast pace. The Scottish Government has set targets of 5 GW installed low carbon hydrogen capacity by 2030, growing to 25 GW by 2045. The analysis of existing and planned hydrogen production projects in Scotland indicates that these targets can be met, but business models are needed to accelerate the development of transport and storage infrastructure, supply chains and skills and attract further investment.

Green hydrogen production clusters are likely to be formed near ScotWind wind farm development sites and there is also significant potential for the production of alternative clean fuels in INTOG regions.

The proximity to European demand, combined with an abundance of offshore wind resources and extensive offshore and coastal infrastructure in Scotland, create a large potential for the export of hydrogen produced in the UK.

The meta-analysis of hydrogen demand in Germany provides a comprehensive overview on various studies on hydrogen demand development in the upcoming years. All studies use different approaches and assumptions to elaborate on this question.

For 2030, consensus among all studies regarding hydrogen demand is rather uniform (42 to 72 TWh).

By 2045, the range of results varies extremely (184 TWh to 694 TWh), reflecting different underlying assumptions concerning the hydrogen economy and infrastructure set up in 2045.

Another important point is that the industrial sector is projected to have the highest hydrogen demand by 2030 and beyond. Within this sector, the basic chemical industry is anticipated to have the highest hydrogen demand, followed by the steel industry. Chemical industry mostly utilises hydrogen for ammonia, methanol, and PVC production, i.e. using it as a feedstock. According to the forecast, the other sectors are expected to realise their ramp-up into hydrogen economy mostly beyond 2030.

The metanalysis findings indicate that Germany could potentially take the whole supply volume exported from Scotland. This is set as an assumption for scenario development.

Figure 28 shows a visual representation of the planned hydrogen hubs in Scotland, a potential **offshore pipeline route** and regional demand in Germany by 2032 based on the market analysis conducted for the draft of the core hydrogen network. This shows the potential match based on supply via an offshore pipeline directly linking Scotland to Germany.

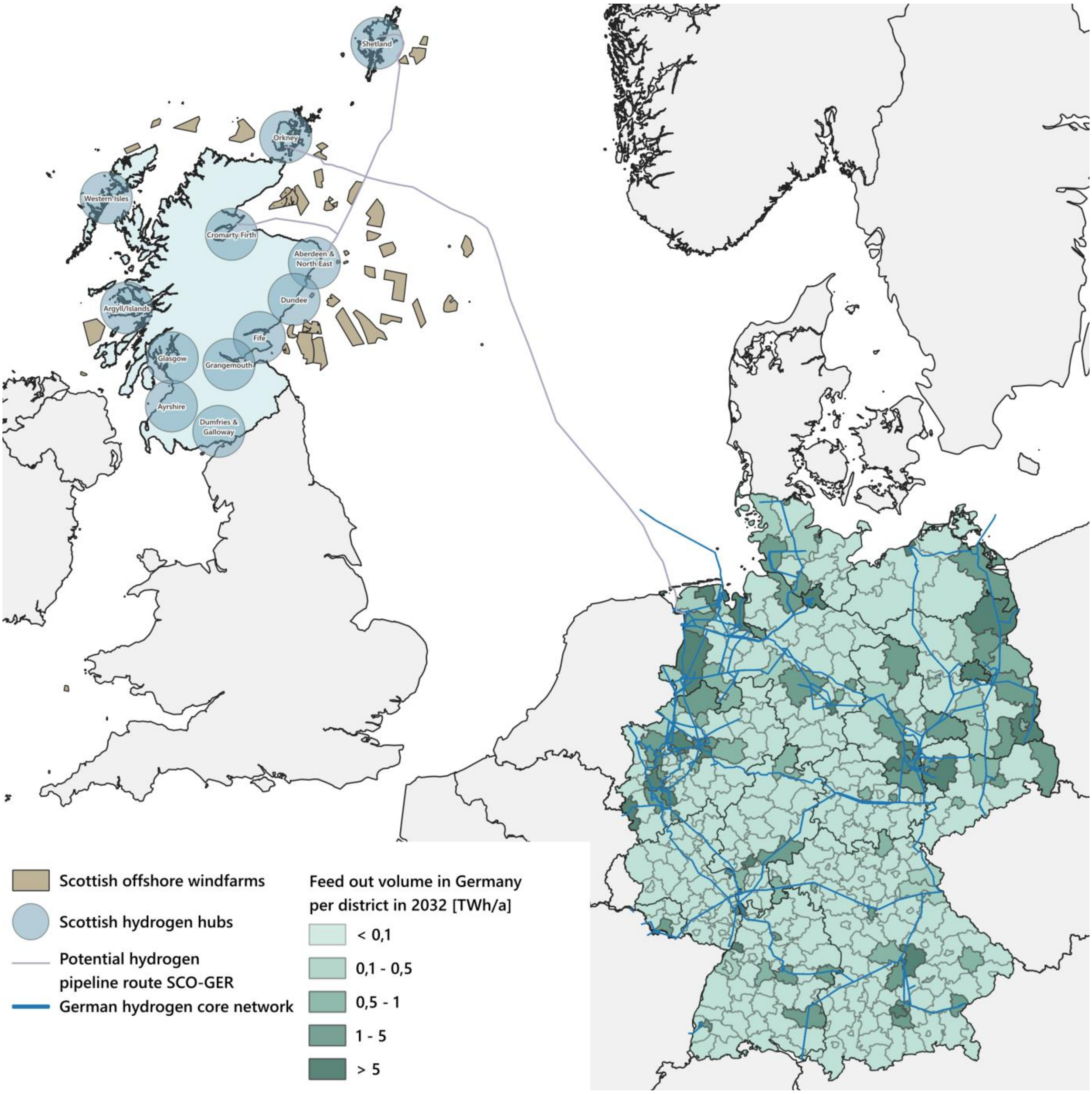

Figure 28: Matching Scottish supply and German Demand via pipeline

For the **ship-based transport**, existing shipping lanes can be used. Figure 29 offers a comprehensive overview of the announced import terminals in Germany and expected export terminals in Scotland. Scotland's port infrastructure and associated supply chains can be adapted to support hydrogen distribution, extending the lifetime of existing terminals and ports. Although plans for the repurposing of the gas transmission system aren't yet in place, the co-location of hydrogen production and export points could significantly simplify the level of adjustment required to enable hydrogen distribution. Plans for hydrogen development should be coordinated to align with export ambitions and international initiatives. In Germany, all terminals are announced to be built by 2030. It should be noted that the terminal sites are close to the hydrogen core network, which is essential to ensure an easy hydrogen transport onshore. In 2027/2028, according to the published information on the hydrogen core network, the pipeline sections connecting all the terminals in the North Sea and Baltic Sea are planned be completed. [53] The ammonia terminals that will be operational before 2027 have announced ammonia supply concepts e.g. by train (cf. Table 9).

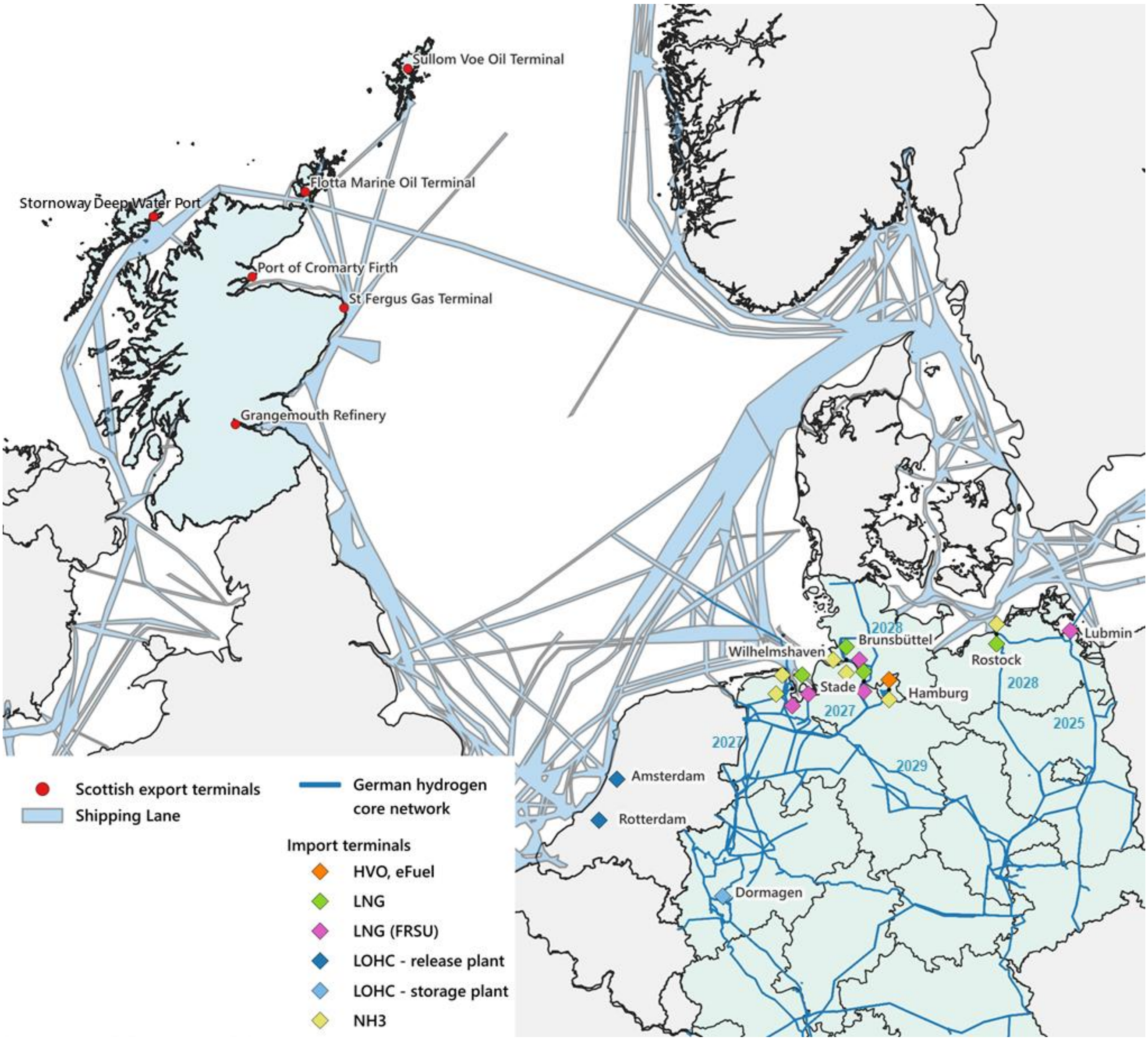

Figure 29: Existing and planned export terminals in Scotland and import infrastructure to Germany

As highlighted in the introduction, the scenario analysis focuses on two pivotal development stages, each crucial for delineating a comprehensive understanding of production and end-use dynamics aligned with the decarbonisation and export strategies of both nations:

Stage 1 (2023 - 2030): Encompassing early production and end-use activities of hydrogen and its derivatives preceding the installation of pipelines.

Stage 2 (2030 - 2045): Involving the commissioning and ramp-up of pipelines to facilitate enhanced distribution.

During **Stage 1**, the focus is on early production and end-use activities in both Scotland and Germany. Without the presence of offshore pipelines, transportation relies on existing infrastructure, such as ships offshore and trains, ships and trucks onshore. Scotland's green hydrogen hubs are anticipated to generate significant volumes of hydrogen, which will need to be efficiently transported to various demand centres in Germany. This stage sets the foundation for the later phases by establishing production capabilities, consumption patterns and trade relations. **Stage 2** marks the commissioning and ramp-up of offshore pipelines connecting Scotland and Germany. With the installation of these pipelines, the distribution of green hydrogen becomes more streamlined and cost-effective. Additionally, Germany's hydrogen core network is expected to be fully operational, further facilitating the integration of green hydrogen into the national energy system.

# 2. Scenario development

## 2.1 Scenario description and analysis

Two scenarios are explored to match hydrogen supply and demand between Scotland and Germany (see Figure 30). The first scenario, Maritime Hydrogen Export to Pipeline Transition, involves a 10 GW pipeline capacity, while the second scenario, Hydrogen Pipeline Scale-up, triples the pipeline capacity to 30 GW. The prioritisation of exported derivatives is based on the supply chain assessment. The analysis investigates multiple facets, including the volume of hydrogen involved, infrastructure requirements and conversion processes versus direct utilisation. These evaluations are crucial for devising an effective strategy that aligns with the dynamic needs of both regions while optimising resource utilisation and ensuring regulatory compliance.

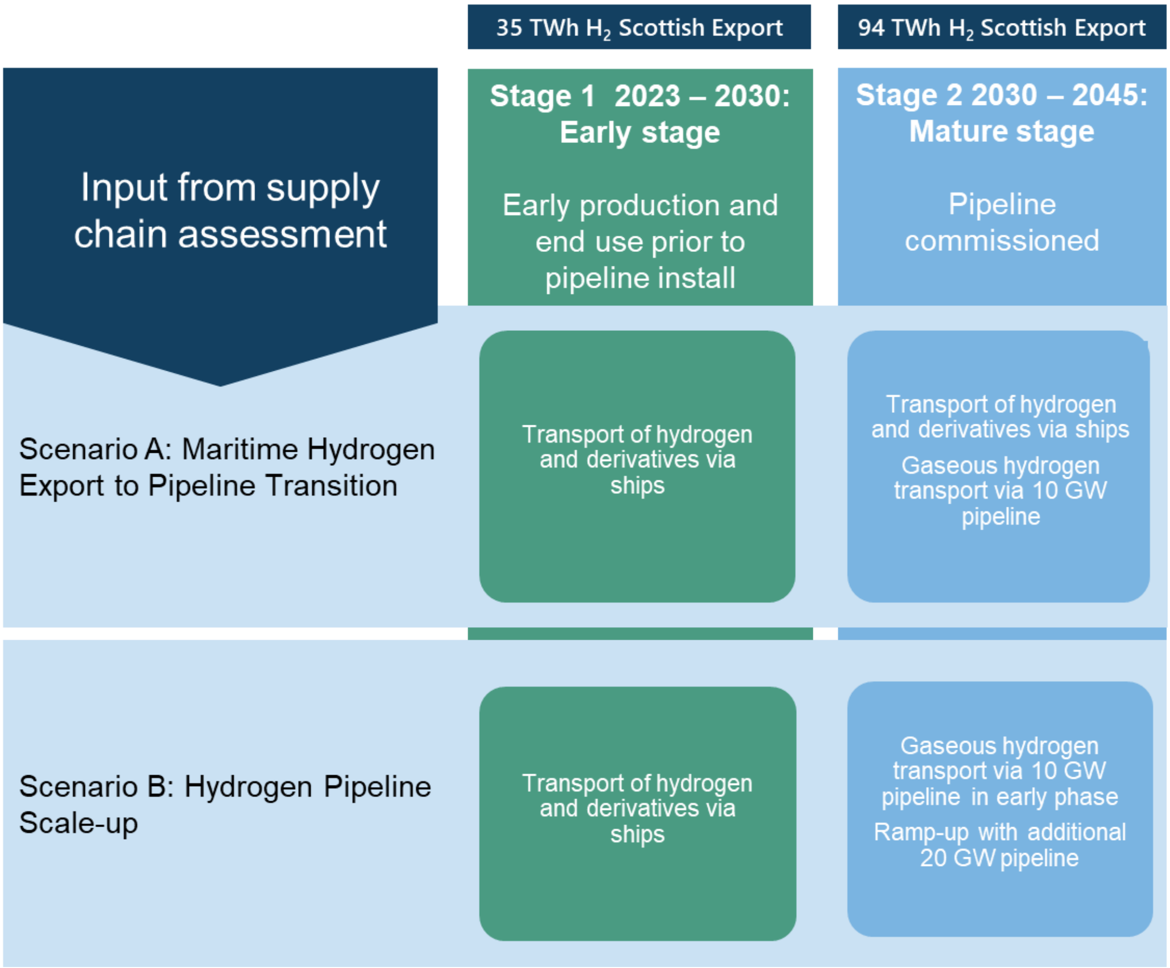

Figure 30: Overview of matching scenarios for hydrogen export between Scotland and Germany

## Scenario A: Maritime Hydrogen Export to Pipeline Transition

In Scenario A, Maritime Hydrogen Export to Pipeline Transition, ammonia stands out as the most feasible option for expediting the development of hydrogen supply chains in Stage 1 leading up to 2030. This is attributed to the planned and progressing infrastructure and transportation capabilities associated with ammonia.

In Stage 2, a ramp-up in the utilisation of ammonia is expected from 2030 onwards. Furthermore, the potential for liquid hydrogen emerges as a promising alternative by the beginning of 2030s, fuelled by both the projected increase in demand and the ongoing advancements in $LH_2$ transportation technologies. The LOHC pathway is also projected to become competitive by the second stage. Approximately 31 TWh of hydrogen could be transported via the 10 GW pipeline, while the remaining 63 TWh would be transported using $NH_3$, $LH_2$, and LOHC (see Figure 31).

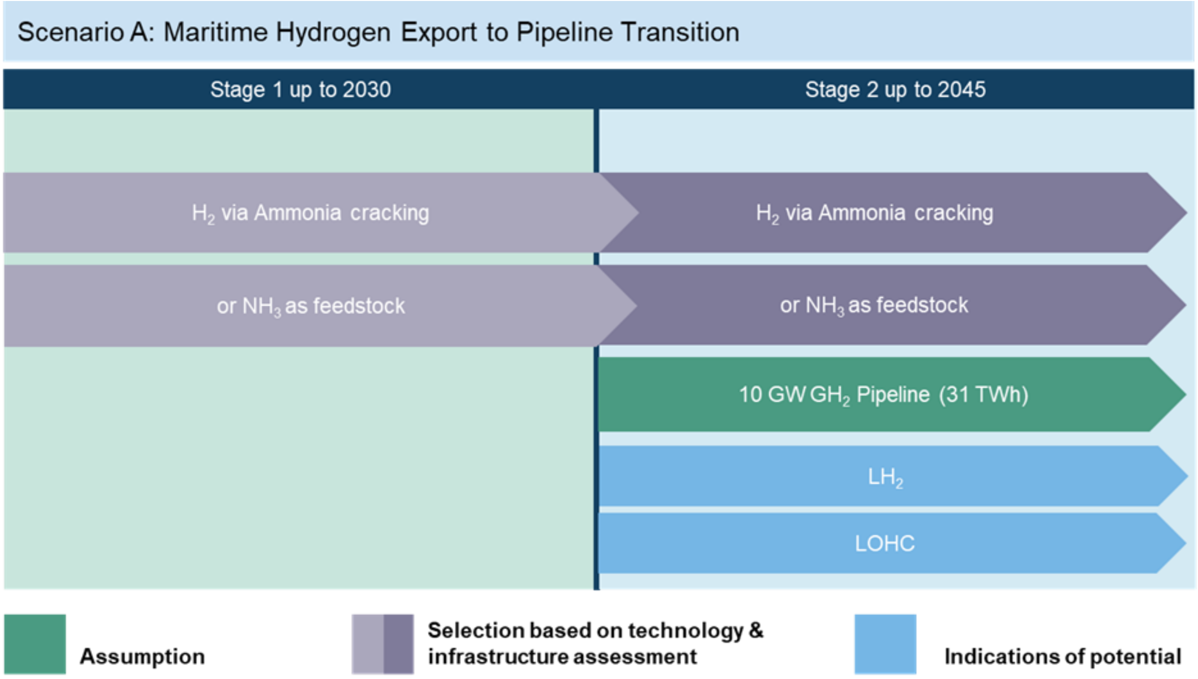

Figure 31: Scenario A: Maritime Hydrogen Export to Pipeline Transition

Stage 1 (up to 2030)

In the first stage, up to 2030, the possible path involves exporting 35 TWh of hydrogen from Scotland to Germany.

Based on the supply chain assessment, the most immediate feasible option is to export **green ammonia** from Scotland to Germany. This is advantageous at an early stage due to the well-established nature of ammonia shipping, but involves several necessary treatment steps. First, ammonia production facilities must be set up in Scotland, requiring access to hydrogen and nitrogen feedstocks or electrolysis and nitrogen generation units on site. This could be achieved through centralised production near the export site or through localised ammonia production at the windfarm site, requiring its subsequent transport to export terminals, where ammonia gets loaded onto ships. Regarding the current status in Scotland, the availability of ammonia production facilities is limited, but early projects are testing the production and transport of ammonia at small scales and efforts are underway to enhance infrastructure and production capacity in line with export demands. The export of hydrogen as ammonia is projected to cost at least £1/kg. [104] Specialised tanker vessels then transport the ammonia across the North Sea to import terminals in Germany. The required number of ships depend on the projected ammonia production volume, the vessel capacity and shipping frequency.

An ammonia import infrastructure is currently planned in Germany as shown in the previous section. The supplied ammonia can either be directly used as a fuel or chemical stock or be cracked back into hydrogen. It is worth noting noteworthy that direct ammonia use is preferable in terms of efficiency. It remains uncertain whether local production in Germany will be prioritised or if import will be favoured. Assuming full availability for Scottish exports, the $NH_3$ import terminal capacity would be sufficient for Scottish export volumes of stage 1 from scenario A & B (see Figure 26).

Stage 2 (2030 to 2045):

In Stage 2, extending until 2045, plans entail the construction of a direct 10 GW pipeline connecting Scotland and Germany, constituting one-third of the potential supply volume. The Hydrogen Backbone Link project route assessment favours the connection of the terminals at Sullom Voe, Flotta, Cromarty Firth and St Fergus to the Emden region in Germany following the existing Europipe I trunkline route. This new build pipeline will have capacity to transport 2,400 t/day, with commissioning in the early 2030s and a CAPEX spend of 2.7 bn GBP expected. It is anticipated that the pipeline won't operate at full capacity initially, as large scale supply of green hydrogen will depend on the wind capacity installed, so a capacity build-up is assumed reaching 90% capacity within 5 years of operation. [88] By allowing the pipeline to operate bellow capacity, the pipeline infrastructure can also be used to provide buffer storage accounting for variations in supply and demand.

In Germany, the hydrogen core network with a feed-in capacity of 100 GW is to be completed by 2032 connecting most essential demand centres. Integrated network planning of gas and hydrogen on a 2- year cycle is expected to further develop the hydrogen core network. In addition, it is expected that most DSOs would seek to make their gas distribution networks carbon neutral by 2045, including hydrogen and other climate-neutral gases. Overall, gas networks at transmission and distribution level would try to reach a large number of potential end-users – first the main ones directly connected to the core network, and then those without access to the core network. All end users connected to a hydrogen network could be potential off-takers of gaseous hydrogen imported from Scotland.

**Liquid hydrogen** appears as a viable option by the early 2030s. Liquefaction is a well-established but energy-intensive process, which requires storage in specialised vessels (Dewars) to minimise boil-off rates. Production facilities need to be established in Scotland and vessels with large capacities (up to 160,000m$^3$) must be developed to enable large scale transport of liquid hydrogen, but there are several industry projects underway. Transportation costs are estimated to be £0.9/kg$H_2$ for 1,000 km journeys, increasing with longer distances. [103]

In Germany, the import terminal technology development is in the early stages of planning and projects for $LH_2$ terminals have not yet been announced. The onshore transportation especially by road is already established. The transportation by train and inland vessels is also very likely possible due to existing railway and waterway networks. There is considerable activity regarding the import and demand of $LH_2$, especially within Northern Germany, and several players are investigating the potential of liquid hydrogen and collaborating to derive viable business cases. Taking into account mobility, aviation and maritime sectors regarding industrial activities and ongoing research projects a strong likelihood of increasing $LH_2$ demand in Germany can be suggested. It could be worth it taking this path into consideration over the next period of time and monitoring actual developments.

The use of **LOHC** for the transport of large quantities of hydrogen is unlikely to be feasible prior to 2030 due to technical challenges associated with the efficiency of the dehydrogenation process, which at present accounts for the largest portion of cost. There would be a cost advantage in the co-location with industrial processes that generate waste heat which could be reused in the dehydrogenation process. The LHyTS project assessed the feasibility of maritime transport of LOHC from Scotland's St Fergus and Sullom Voe terminals to Rotterdam in the form of methylcyclohexane (MCH). Both port facilities in Scotland were considerable suitable for the co-location of hydrogen production, hydrogenation and storage, with subsequent large-scale export by sea on tanker ships. The cost analysis for a small-scale (40,100 t/year) and a large-scale (250,500 t/year) scenario resulted in an expected cost of transport of £4,80/kg$H_2$ and £2.56/kg$H_2$ respectively, assuming an operational period of 20 years. [89] The current project landscape of LOHC import terminals shows announced terminals in Amsterdam and Rotterdam with a planned total capacity of around 41,000 t/a $H_2$. Export to Germany would involve a similar transport distance, but the volume and number of shipments should take into consideration individual port restrictions at the export and import sites to guarantee an efficient and secure supply.

Throughout Stage 2, advancements in technology will facilitate the development of nearly all hydrogen supply chains up to 2045. However, the precise configuration in terms of volumes remains uncertain and will be contingent upon market dynamics and evolving industry needs.

# Scenario B: Hydrogen Pipeline Scale-up

In Scenario B, Hydrogen Pipeline Scale-up, as with Scenario A, ammonia stands out as the most feasible option for expediting the development of hydrogen supply chains in Stage 1 leading up to 2030. This is attributed to the planned and progressing infrastructure and transportation capabilities associated with ammonia.

Progressing to Stage 2, the 10 GW hydrogen pipeline is expected to become operational in the early 2030s, capable of delivering approximately 31 TWh of hydrogen to various end users. Concurrently, the ammonia-based infrastructure established in the first phase will continue to be leveraged. Following this, a second pipeline with a capacity of 20 GW would be launched, aimed at supporting the rising supply and demand for hydrogen projects (See Figure 32).

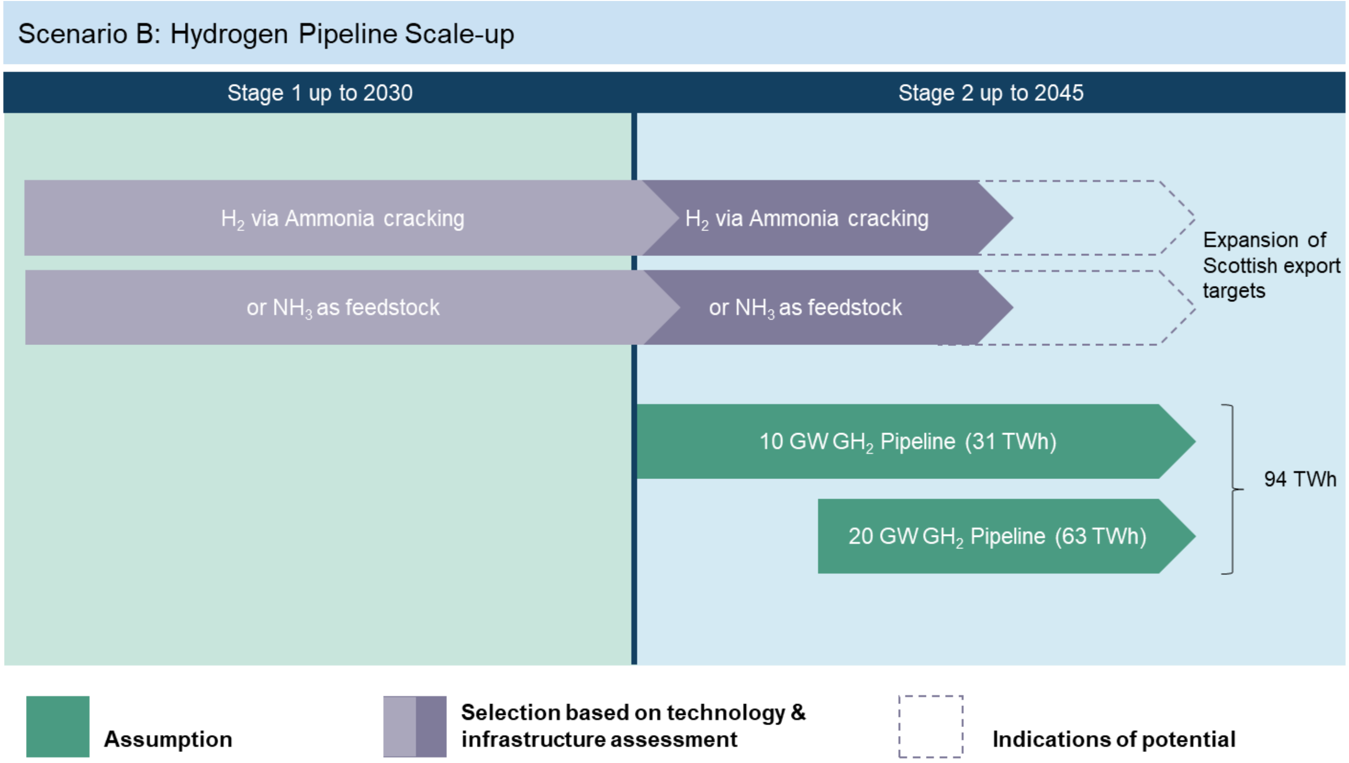

Figure 32: Scenario B: Hydrogen Pipeline Scale-up

Stage 1 (up to 2030)

Similar to the early stage in scenario A hydrogen export from Scotland to Germany amounts to 35 TWh hydrogen via maritime transport, utilising existing infrastructure and logistical frameworks. Ammonia is preferred due to readily available infrastructure.

Stage 2 (2030 to 2045):

Stage 2 witnesses the early deployment of a 10 GW pipeline, strategically addressing the escalating demand for hydrogen. As the demand continues to rise, a pivotal transition period ensues, integrating both the 10 GW pipeline and an additional 20 GW (70 TWh/y) pipeline capacity into the hydrogen transportation network between Scotland and Germany. This integration approach optimises infrastructure utilisation, securing a consistent supply of hydrogen at the lowest possible cost to end-users.

Several large-scale transmission projects are already under consideration in the UK, involving a combination of new-build pipelines and reuse of National Transmission System pipelines. Infrastructure repurposing can deliver high cost savings in comparison to full new build options, but timelines for the decommissioning of different sections of the National Transmission System and offshore pipelines can vary, with an impact on the timeline for development of the additional pipelines.

The definition of optimal routes and landfall options for hydrogen distribution should take into account the location of existing production and demand hubs as well as existing distribution infrastructure onshore and offshore. Daisy chaining of existing offshore gas pipelines could enable pipeline developments where up to 80% of pipeline infrastructure is reused, but a detailed assessment of line sizes and materials would be required and could add significant complexity to route development. [104] Onshore routes should additionally take into account the complexity of delivery within or near urban areas. With a number of initiatives planning the development of new hydrogen pipelines at both national and international scale, it is crucial to support the development of business and funding models as well as ownership structures that enable partnerships across the value chain of international infrastructure development. This can help ensure pace of delivery and provide clarity to investors, preventing duplication of effort.

Key considerations during this stage include:

- Duration of permit procedures for offshore pipelines crossing the German EEZ and coastal waters, where different authorities have oversight.
- Timing the transition to incorporate both pipelines effectively, ensuring a seamless and efficient distribution network.
- Commissioning of additional 20 GW of pipeline capacity enables the delivery of the Scottish export ambition in full, with previously established ammonia export supporting an increased ambition in terms of export targets in line with demand trends.

### 2.2 Scenario evaluation

In this section, a comparative analysis of the two scenarios is conducted. Each scenario presents unique drivers, challenges, and considerations for infrastructure development and market penetration as shown in Table 16. The evaluation is centred around eight categories where similarities and nuances are identified.

Table 16: Scenario comparison across categories

| Category | Scenario A | Scenario B |
|---|---|---|
| **Market Entry Strategy** | Both scenarios prioritise early market entry through the ammonia pathway, providing flexibility to adapt to evolving market needs. Additionally, the establishment of dedicated hydrogen pipelines, ensures direct and efficient transportation. | |
| **Infrastructure Development** | Scenario A requires investment in diversifying export pathways, especially in stage 2, potentially with lower upfront costs. | Scenario B necessitates significant initial capital for pipeline construction and infrastructure development, but promises enhanced long-term resilience and reliability. |
| **Collaborative Efforts** | Both scenarios offer the opportunity of collaboration potential between Scotland and Germany and others to enhance infrastructure and streamline logistics for hydrogen export, ensuring mutual benefits. | |
| **Flexibility and Adaptability** | Scenario A offers flexibility through diversified export pathways. | Scenario B provides long-term scalability and reliability through enhanced pipeline capacity, but may lack flexibility compared to maritime transport methods. |
| **Regulatory and Permitting Challenges** | Both scenarios encounter regulatory hurdles and permitting delays associated with infrastructure development, potentially impacting project timelines and compliance costs. | |

<table>
<tr><td></td><td colspan="2">Further points to consider: Review applicable laws, regulations and policy conditions that may affect market entry, such as trade barriers, certification requirements and taxes.</td></tr>
<tr><td rowspan="2"><b>Market Competition</b></td><td colspan="2">Both scenarios encounter competition from alternative sources of supply, particularly from countries with which Germany has established hydrogen cooperation agreements. These countries are located across the globe, characterized by their abundant renewable energy resources. Notably, this includes regions in Australia, South America, North America, and both Northern and Southern Africa, in addition to countries situated in southern, northern, and eastern Europe.</td></tr>
<tr><td>Competitors scenario A:<br>Competitors encompass all other $NH_3$ exporting countries targeting Germany as their destination. In addition to Europe and North Africa, North and South America as well as the Middle East are potential regions of origin for green ammonia. Additionally, on the $LH_2$ or LOHC pathways, there would be competitors from outside Europe.</td><td>Competitors scenario B:<br>Competitors would be mostly based in Europe, creating opportunities for partnerships particularly surrounding infrastructure development. Countries which also supply $GH_2$ by pipeline to Germany – either via the North Sea or Baltic sea corridor or from Eastern / Southern Europe.</td></tr>
<tr><td><b>Political framework</b></td><td colspan="2">Both scenarios rely on political frameworks for market access and infrastructure utilisation.</td></tr>
<tr><td><b>Cost-effectiveness and Risk Management</b></td><td>Scenario A may limit infrastructure investment risks, offer cost-effectiveness through diversification and risk reduction strategies.</td><td>Scenario B prioritises long-term cost-effectiveness through pipeline ramp-up and infrastructure expansion.</td></tr>
<tr><td><b>Market potential</b></td><td colspan="2">The demand for $NH_3$ is relatively uncertain both in terms of quantity and utilisation, whether for energy or feedstock purposes. Investing in $NH_3$ entails risks associated with being an early mover in a potentially volatile market.<br>Despite the uncertainties, $NH_3$ still presents an opportunity for those willing to navigate early mover challenges, establish customer relationships and build up a market share in Germany for green hydrogen derivates.<br>Taking into account mobility, aviation and maritime sectors regarding industrial activities and ongoing research projects a strong likelihood of increasing $LH_2$ demand in Germany can be suggested.<br>It is widely acknowledged that Germany will require $GH_2$ post-2030, ensuring a consistent and predictable demand. Given the assured demand for $GH_2$, investing in this pathway offers a relatively secure market opportunity.</td></tr>
</table>

In conclusion, the choice between Scenario A and Scenario B hinges on factors such as upfront investment capabilities, market preferences, regulatory environments, and risk tolerance. Each scenario presents distinct opportunities and challenges, requiring careful consideration to align with the overarching goals of the hydrogen supply chain between Scotland and Germany and requiring further analysis of the identified pathways.

# Conclusions and recommendations

This study aims to bridge the gap between projected green hydrogen production in Scotland and demand centres in Germany, emphasising the potential for collaboration between the two nations. Scotland's abundant renewable energy resource complements Germany's substantial demand for green molecules, presenting a compelling opportunity for mutually beneficial partnerships.

As hydrogen production capability develops in Scotland, the creation of export routes to fulfil European demand becomes a catalyst for commercial deployment and supply chain capability improvement. The analysis of the early green hydrogen production project pipeline shows that installed capacity will increase at a fast pace, in line with offshore wind deployment, highlighting the importance of straightforward routes to market and the potential for diversification of energy sources in line with decarbonisation strategies.

Considering the variety of studies with different focuses leading to diverging predictions for hydrogen demand in Germany, a metanalysis was conducted and supplemented with an assessment of current announcements of supply and demand projects. Key findings emphasise Germany's significant demand for hydrogen, with imports from Scotland having the potential of covering an important share of the import volumes.

For 2030, consensus among all studies regarding hydrogen demand in Germany is rather uniform (42 to 72 TWh). By 2045, the range of results varies extremely (184 TWh to 694 TWh), reflecting different underlying assumptions regarding the hydrogen economy and infrastructure set up in 2045. A similar pattern is identified for import shares with volumes varying between 0 TWh and 46 TWh in 2030 and between 78 TWh and 422 TWh in 2045. **Results indicate that prospective Scottish hydrogen exports could potentially satisfy 22 to 100 % of Germany's hydrogen import volume in 2045.**

The critical element to realise this collaboration lies in the establishment of Pan North Sea transport infrastructure. Options such as $GH_2$, $LH_2$, $NH_3$, SNG and LOHC offer promising avenues to facilitate the efficient and sustainable transportation of green hydrogen between Scotland and Germany.

Up to 2030, $GH_2$ carriers for offshore transport are undergoing development but are not considered an alternative to pipeline transport since high quantities cannot be transported. Additionally, no $LH_2$ or LOHC import terminals have been announced in Germany. Furthermore, the production of synthetic methane presents technical challenges primarily related to $CO_2$ capture and utilization and is not currently being produced in the UK. Overall, **ammonia emerges as the most feasible option for accelerating the establishment of hydrogen supply chains towards 2030**, with its infrastructure and transportation capabilities already well-planned and progressing.

Up to 2045, technological advancements are anticipated to pave the way for the comprehensive establishment of hydrogen supply chains by 2045. This progress will see pipeline infrastructure supporting the transport of gaseous hydrogen, further enhancements in ammonia utilisation, the potential for $LH_2$ import terminals to accommodate increasing demand, and the establishment of a mature infrastructure for LOHCs.

Ammonia emerges as a suitable option to accelerate supply chains for green hydrogen from Scotland into the German market up to 2030 in both scenarios. However, the precise configuration in terms of volumes remains uncertain and will be contingent upon market dynamics and evolving industry needs. Scenario A, Maritime Hydrogen Export to Pipeline Transition, involves a 10 GW pipeline capacity, while scenario B, Hydrogen Pipeline Scale-up, triples the pipeline capacity to 30 GW. Scenario A offers a more diversified configuration by setting on diversified export pathways ($GH_2$, $LH_2$, $NH_3$ and LOHC) thereby ensuring flexibility and generating market opportunities. Scenario B on the other hand sets on higher pipeline volumes securing long-term scalability and reliability as well as cost effectiveness.

In order for Scotland to become a key supplier for the rapidly growing hydrogen demand in Germany, key fields of action aimed at facilitating the development of the hydrogen supply chain between Scotland and Germany are identified. These field of actions aim to address challenges, capitalise on opportunities, and provide guidance towards effective decision-making and action:

- Research, Monitoring, and Modelling:

Conduct a comprehensive assessment of identified pathways outlined in scenarios A and B through a dedicated feasibility study. This study should analyse the feasibility, economic viability, and environmental impacts of each pathway to inform decision-making. The Hydrogen Backbone Link Project 2.0 will further analyse the pipeline routing options and provide guidance for needed next steps.

- Investment in Technology Innovation

  The development of cost-effective technologies across the entire hydrogen production value chain is fundamental to unlock the potential of hydrogen and support the scale and pace of deployment required to fulfil national targets and place Scotland at the heart of Europe's near and long-term decarbonisation strategy.

- Investment in Infrastructure and Financing:

  Prioritize the development of a comprehensive hydrogen and derivatives infrastructure, encompassing export terminals and pipeline networks, to bolster the hydrogen supply chain between Scotland and Germany, leveraging the foundational Hydrogen Hubs initiative. To facilitate and secure these investments, advocate for a robust regulatory framework that aligns with industry standards and promotes compliance. Simultaneously, aim to attract both public and private investment in hydrogen projects by offering financial incentives such as subsidies, loan guarantees, and tax breaks, thereby encouraging further development in hydrogen infrastructure and technological innovation.

- Energy Partnerships:

  Strengthen bilateral partnerships with Germany at both political and infrastructure levels to foster collaboration and support the development of hydrogen infrastructure. Facilitate partnerships between producers in Scotland and off-takers in Germany to establish reliable supply chains and market access. This involves establishing joint ventures, consortiums, and public-private partnerships to share knowledge, resources, and best practices.

- Export Targets:

  Explore the opportunity to expand Scottish export ambition, alongside domestic markets, in alignment with the considerable hydrogen demand in target markets, thereby maximising export potential and avoiding stranded investments. Continuously reassess export targets based on evolving market dynamics and demand trends.

- Policy and Regulation Alignment:

  Ensuring that policies and regulations in both Scotland/UK and Germany are aligned to support the development of a hydrogen supply chain. This involves creating a supportive regulatory framework, including incentives, such as carbon pricing mechanisms to encourage investment in hydrogen infrastructure.

- Subsidy Mechanisms for Early Projects

  Development of subsidy of incentives programmes for early hydrogen export projects are important to bring costs down to a competitive level. Project finance mechanisms will help distribute risk and reduce equity, driving investor confidence and accelerating market development.

The Hydrogen Backbone Link Phase 2 will further analyse development options for offshore pipeline transport of hydrogen, including routing and configuration, assessment of associated systems, safety requirements and economics.

Project MOHN will further explore distribution network development in Germany and focus on understanding the needs and interests of relevant German stakeholders from industry and academia regarding potential hydrogen cooperation with Scotland and further mapping the hydrogen demand.

By leveraging these insights and implementing targeted action plans, Scotland and Germany can pave the way for a vibrant and interconnected green hydrogen economy, contributing to the global transition towards sustainable energy systems.

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# Appendix

Table 17 lists the studies that were analysed for German hydrogen demand. Short name represents the name used in the graphs.

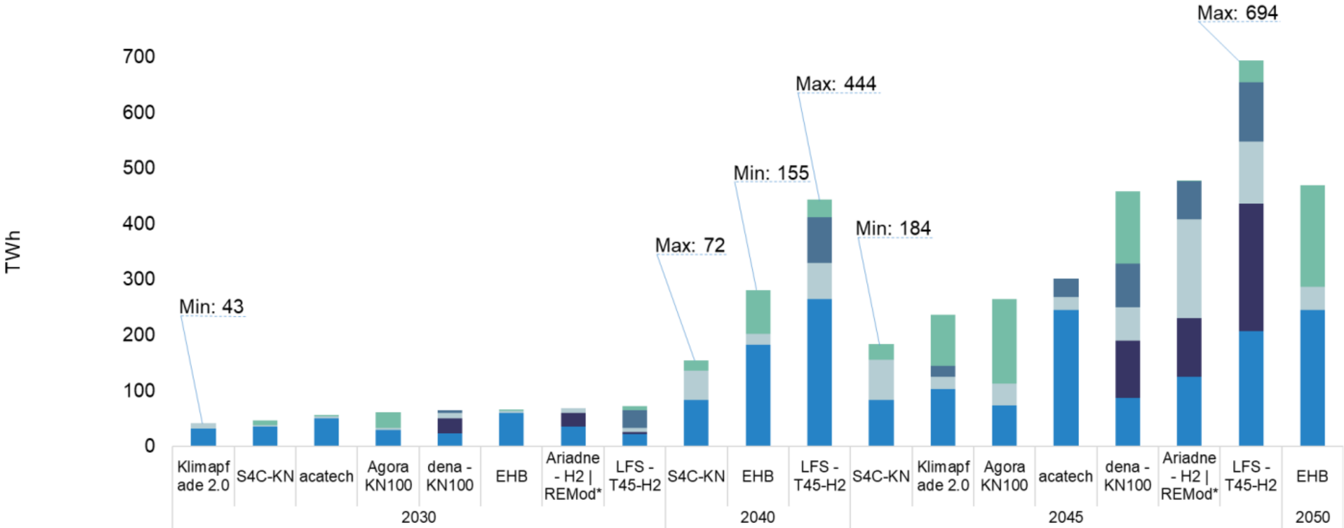
Table 17: Analysed studies for the German hydrogen demand [10, 33, 54, 58, 78, 83, 94, 102]

| **Study** | **Ariadne-Report: Deutschland auf dem Weg zur Klimaneutralität 2045 - Szenarien und Pfade im Modellvergleich** | **dena-Leitstudie Aufbruch Klimaneutralität** | **Klimaneutrales Deutschland 2045. Wie Deutschland seine Klimaziele schon vor 2050 erreichen kann** | **Langfristszenarien für die Transformation des Energiesystems in Deutschland 3** |
|---|---|---|---|---|
| Abbreviated name | Ariadne - H2 \| REMod* | dena - KN100 | Agora KN2045 | LFS - T45-H2 |
| Analysed scenario | H2 \| REMod* | KN100 | | T45-H2 |
| Published | 2021 | 2021 | 2021 | 2023 |
| Author | Kopernikus-Projekt Ariadne | Deutsche Energie-Agentur (dena) | Prognos; Öko-Institut; Wuppertal-Institut | Consentec GmbH; Fraunhofer-Institut für System- und Innovationsforschung ISI; ifeu – Institut für Energie- und Umweltforschung Heidelberg; Technische Universität Berlin |
| Institutions | Kopernikus-Projekt Ariadne; Potsdam-Institut für Klimafolgenforschung (PIK) | Deutsche Energie-Agentur (dena) | Prognos; Öko-Institut; Wuppertal-Institut | Consentec GmbH; Fraunhofer-Institut für System- und Innovationsforschung ISI; ifeu – Institut für Energie- und Umweltforschung Heidelberg; Technische Universität Berlin |
| Time horizon | 2030 - 2045 | 2030 - 2045 | 2030 - 2045 | 2025 -2030 - 2035 - 2040 - 2045 |
| Sectors or import/ domestic production | Sectors, import/ domestic production | Sectors | import/ domestic production | Sectors, import/ domestic production |
| Methodology | Study presents concrete transformation paths to climate neutrality by 2045, with a total of six target achievement scenarios. Different technology orientations lead to varying of transformation challenges. This meta-analysis only | Practice-orientated "bottom-up" perspective. Four key aspects are central to the modelling approach: a high level of ambition for energy efficiency, extensive direct use of renewable energies, widespread adoption of | Study focuses on a technology scenario to reach greenhouse gas neutrality by 2045- as further acceleration of efficiency advances has reached its limits from today's perspective. The main criterion for evaluation is | The study encompasses modelling of the whole energy system. It involves further calculations updating the TN scenarios. This meta-analysis focuses on the T45-H2 scenario, which is based on a strong utilisation of hydrogen. |

| | | | |
|---|---|---|---|
| | focuses on the hydrogen scenario. | powerfuels and the management of natural and technical $CO_2$ -emissions. | economic efficiency. |

| Study | EUROPEAN HYDROGEN BACKBONE; Analysing future demand, supply, and transport of hydrogen | **Klimapfade 2.0 – Ein Wirtschaftsprogramm für Klima und Zukunft** | **Szenarien für ein klimaneutrales Deutschland. Technologie-umbau, Verbrauchs-reduktion und Kohlenstoffmanagement** | **Treibhausgasneutralität in Deutschland bis 2045 Ein Szenario aus dem Projekt SCI4climate.NRW** |
|---|---|---|---|---|
| Abbreviated name | EHB | Klimapfade 2.0 | acatech | S4C-KN |
| Analysed scenario | | | main scenario | |
| Published | 2021 | 2021 | 2023 | 2023 |
| Author | Guidehouse | Bosten Consulting Group (BCG) | Mario Ragwitz; Anke Weidlich; et al. | SCI4climate.NRW |
| Institutions | European Hydrogen Backbone (EHB) | BDI | Nationale Akademie der Wissenschaften Leopoldina; acatech - Deutsche Akademie der Technikwissenschaften; Union der deutschen Akademien der Wissenschaften | SCI4climate.NRW; Wuppertal Institut; Institut der deutschen Wirtschaft |
| Time horizon | 2030 - 2040 - 2050 | 2030 - 2045 | 2020 - 2030 -2045 | 2030 - 2040 - 2045 |
| Sectors or import/ domestic production | Sectors | Sectors, import/ domestic production | Sectors, import/ domestic production | Sectors, import/ domestic production |
| Methodology | Analysis of the European hydrogen market in relation to the European hydrogen backbone initiative. Demand projections are provided for all European countries, including Germany. | Follows on from the study "Klimapfade für Deutschland". The aim is to develop a mix of climate policy instruments that would enable the climate targets to be achieved in all sectors in 2030 and set the most important course towards greenhouse gas neutrality in 2045. The emphasis is set on the need for a substantial German hydrogen economy with international connections. | Follow-up study focusing on the transformation of the energy system through model calculations. The study highlights the necessity of far-reaching and rapid technological transformation across all sectors, considering efficiency increase and sufficiency measures. | The study focuses on future developments in energy-intensive industry, analysing their role in achieving climate-neutrality Germany in 2045 in the context of an overall economic transformation path. As part of the creation of the S4C-KN scenario, detailed bottom-up modelling was carried out in particular for the transformation of the basic materials sector. |

Figure 33 corresponds to Figure 13 with the underlying data providing the results of the meta-analysis of German hydrogen demand.



| | Klimapfade 2.0 | S4C-KN | acatech | Agora KN100 | dena - KN100 | EHB | Ariadne - H2 \| REMod* | LFS - T45-H2 | S4C-KN | EHB | LFS - T45-H2 | S4C-KN | Klimapfade 2.0 | Agora KN100 | acatech | dena - KN100 | Ariadne - H2 \| REMod* | LFS - T45-H2 | EHB |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2030 | | | | | | | | 2040 | | | 2045 | | | | | | | 2050 |
| 🟩 power | | 9 | 3 | 28 | | 3 | | 7 | 18 | 78 | 32 | 28 | 92 | 152 | | 130 | 1 | 39 | 183 |
| ■ buildings | | | | | 5 | | | 32 | | | 82 | | 20 | | 33 | 79 | 68 | 107 | |
| ■ transport | 10 | 2 | 3 | 4 | 9 | 3 | 8 | 8 | 53 | 20 | 65 | 72 | 21 | 39 | 23 | 59 | 178 | 111 | 42 |
| ■ industry (feedstock) | | | | | 27 | | 25 | 4 | | | | | | | | 103 | 105 | 229 | |
| ■ industry | 32 | 36 | 51 | 30 | 24 | 61 | 36 | 22 | 84 | 183 | 265 | 84 | 104 | 74 | 246 | 88 | 126 | 208 | 245 |

Figure 33: Sectoral German hydrogen demand from 2030 to 2050 (including data)

Table 18 describes the conversion of the TRL-scale by IEA [67] to the TRL-scale by European Commission [46]. The conversion bases on own assumptions.

Table 18: Conversion of IEA-TRL-scale to EU-TRL-scale

| TRLs | IEA | | | TRL | European Commission |
|---|---|---|---|---|---|
| **11** | Mature | Proof of stability reached | Predictable growth | 9 | Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space |
| **10** | Market uptake | Integration needed at scale | Solution is commercial and competitive but needs further integration efforts | | |
| **9** | | Commercial operation in relevant environment | Solution is commercially available, needs evolutionary improvement to stay competitive | 8 | System complete and qualified |
| **8** | Demon-stration | First of a kind commercial | Commercial demonstration, full-scale deployment in final conditions | | |
| **7** | | Pre-commercial demonstration | Prototype working in expected conditions | 7 | System prototype demonstration in operational environment |
| **6** | Large prototype | Full prototype at scale | Prototype proven at scale in conditions to be deployed | 6 | Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies) |
| **5** | | Large prototype | Components proven in conditions to be deployed | 5 | Technology validated in relevant environment (industrially relevant |

| | | | | | |
|---|---|---|---|---|---|
| | | | | | environment in the case of key enabling technologies) |
| **4** | Small prototype | Early prototype | Prototype proven in test conditions | 4 | Technology validated in lab |
| **3** | Concept | Concept needs validation | Solution needs to be prototyped and applied | 3 | Experimental proof of concept |
| **2** | | Application formulated | Concept and application of solution have been formulated | 2 | Technology concept formulated |
| **1** | | Initial idea | Basic principles have been defined | 1 | Basic principles observed |

# List of Figures

# List of Tables