Scottish Offshore Wind to Green Hydrogen Opportunity Assessment

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EXECUTIVE SUMMARY

Summary of Key Findings

- Scotland has an abundant offshore wind resource that has the potential to be a vital component in our net zero transition. If used to produce green hydrogen, offshore wind can help abate the emissions of historically challenging sectors such as heating, transport and industry.
- The production of green hydrogen from offshore wind can help overcome Scotland's grid constraints and unlock a massive clean power generation resource, creating a clean fuel for Scottish industry and households and a highly valuable commodity to supply rapidly growing UK and European markets.
- The primary export markets for Scottish green hydrogen are expected to be in Northern Europe (Germany, Netherlands & Belgium). Strong competition to supply these markets is expected to come from green hydrogen produced from solar energy in Southern Europe and North Africa.
- Falling wind and electrolyser costs will enable green hydrogen production to be cost-competitive in the key transport and heat sectors by 2032. Strategic investment in hydrogen transportation and storage is essential to unlocking the economic opportunity for Scotland.
- Xodus' analysis supports a long-term outlook of LCoH falling towards £2/kg, with an estimated reference cost of £2.3 /kg in 2032 for hydrogen delivered to shore.
- Scotland has extensive port and pipeline infrastructure that can be repurposed for hydrogen export to the rest of UK and to Europe. Pipelines from the '90s are optimal for this purpose as they are likely to retain acceptable mechanical integrity and have a metallurgy better suited to hydrogen service. A more detailed assessment of export options should be performed to provide a firm foundation for early commercial green hydrogen projects.
- There is considerable hydrogen supply chain overlap with elements of parallel sectors, most notably, the oil and gas, offshore wind and subsea engineering sectors. Scotland already has a mature hydrocarbon supply chain which is engaged in supporting green hydrogen. However, a steady pipeline of early projects, supported by a clear, financeable route to market, will be needed to secure this supply chain capability through to widescale commercial deployment.
- There are gaps in the Scottish supply chain in the areas of design, manufacture and maintenance of hydrogen production, storage and transportation systems. Support, including apprenticeships, will be needed to develop indigenous skills and capabilities in these areas.
- The development of green hydrogen from offshore wind has the potential to create high value jobs, a significant proportion which are likely to be in remote, rural/coastal communities located close to offshore wind resources. These can serve as an avenue for workers to redeploy and develop skills learned from oil and gas, in line with Just Transition principles.

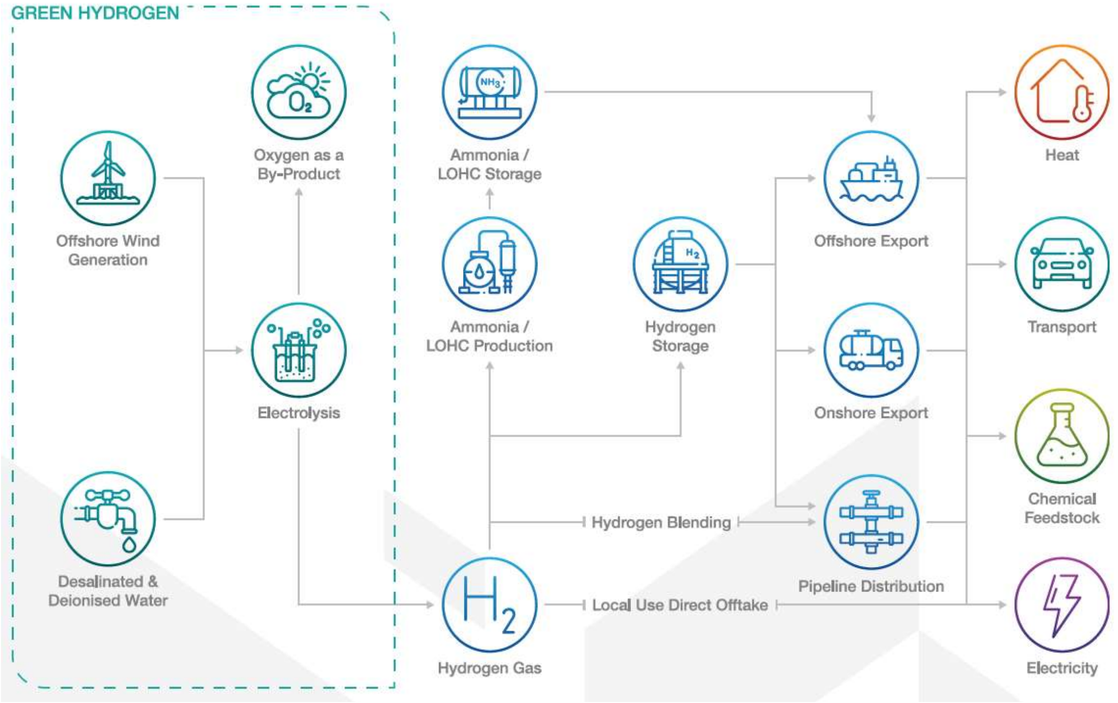
Introduction

The Scottish Government's newly published Offshore Wind Policy Statement sets out a vision for up to 11GW of Scottish offshore wind capacity by 2030. Scotland's extensive offshore wind resource offers considerable potential to support decarbonisation of many facets of the energy system via increased electrification and/or the displacement of existing fossil fuel-based systems with green hydrogen alternatives. Offshore wind coupled with green hydrogen production could not only unlock significant Scottish offshore wind resource in regions with constrained electricity grids, but also significantly contribute towards national and international net-zero targets by decarbonising 'hard-to-abate' sectors such as heat, industry and transport, as well as providing surplus green hydrogen to continental Europe.

The route to market for offshore wind projects supplying electricity to the grid is already well established. However, there is growing interest from industry and policymakers in exploring and enabling routes to market for the large-scale production of hydrogen from offshore wind, including for potential export. This opportunity was highlighted in the recent Offshore Renewable Energy Catapult (OREC) 'Offshore Wind and Hydrogen: Solving the Integration Challenge' report, which estimated that up to 240GW of offshore wind could be deployed in the UK by 2050 for the purpose of producing green hydrogen for export to Europe.

Xodus Group ('Xodus') was commissioned by Scottish Government, Scottish Enterprise, Highlands and Islands Enterprise and a consortium of industrial partners led by EMEC to provide an initial assessment of Scotland's opportunity to produce green hydrogen from offshore wind. This study complements the Scottish Government's Hydrogen Assessment (SHA), which takes a broader view of hydrogen's role as an energy vector and its potential contribution to Scotland's energy transition.

In the course of the study, Xodus conducted a supply chain survey and developed a database of Scottish companies active in the green hydrogen sector, or with aspirations to become so. Xodus would like to acknowledge the support kindly provided by Scottish Enterprise, Highlands and Islands Enterprise, SHFCA, DeepWind and many others in undertaking this survey.



Scotland's Potential

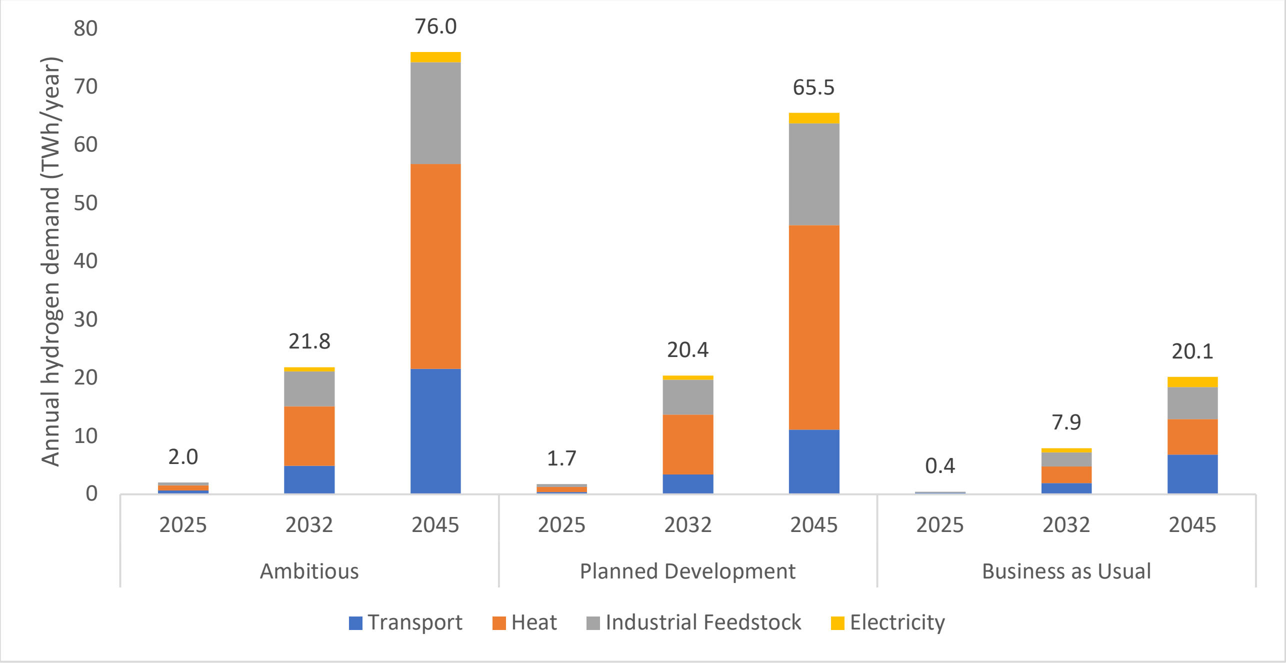
The current forecast from the UK Committee on Climate Change for global low-carbon hydrogen demand varies between 35-1,100 TWh/year in 2030, scaling up to 300-19,000 TWh/year by 2050. Considering that more than 95% of global hydrogen supply is currently produced from fossil fuels, the opportunity for zero-carbon hydrogen produced by large-scale electrolyser systems is enormous.

Scotland is one of the leading nations in green hydrogen, having developed the world's first hydrogen production system from tidal energy (Surf'n'Turf, 2017), and incorporated anaerobic digestion (AD), combined heat and power (CHP) and electrolysis to produce and utilise hydrogen and oxygen as part of the Outer Hebrides Local Energy Hub (OHLEH). These are examples of multiple pioneering Scottish hydrogen projects, which also include the world's first hydrogen-powered double decker bus fleet in Aberdeen. With increasing domestic and international demand for hydrogen, offshore wind coupled with electrolysis presents a green solution with potential to address large scale demand. Scotland has a growing offshore wind sector, but with increased requirements for grid infrastructure upgrades and curtailment risk, hydrogen production could act as an alternative revenue stream to electricity supply to support continued offshore wind development, whilst serving to decarbonise 'difficult-to-abate' sectors.

Hydrogen Demand Projections

Three scenarios were created to explore the development of hydrogen demand in Scotland:

- **Ambitious:** Full transition towards a hydrogen economy in Scotland. This scenario is based on a combination of the most ambitious projections for each sector from the SHA.
- **Planned Development:** Scenario based on wide-ranging hydrogen technology deployment and use across various sectors. This scenario was aligned with Scenario A: 'Hydrogen Economy' from the SHA.
- **Business as Usual:** Conservative scenario with modest hydrogen use and extensive electrification across all sectors. This scenario was aligned with Scenario C: 'Focused Hydrogen' from the SHA.

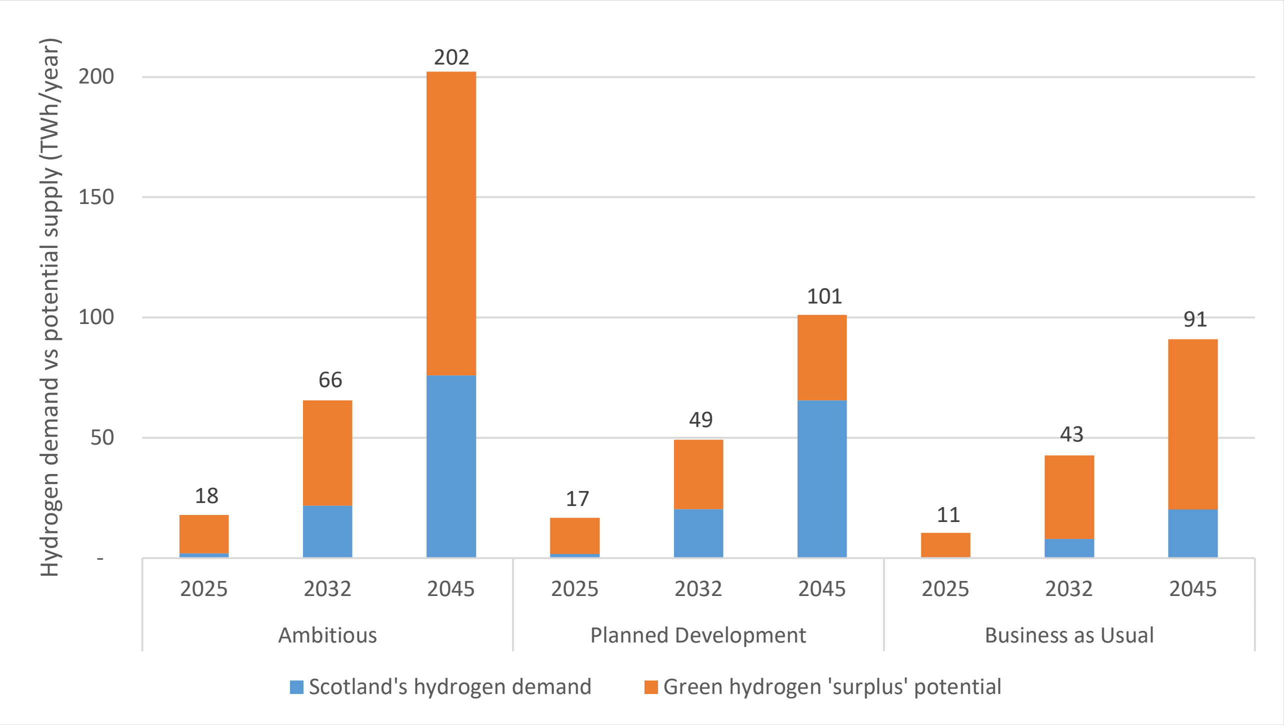


Hydrogen Production Projections

Corresponding scenarios were developed for the potential supply of green hydrogen from offshore wind in Scotland in the period up to 2045:

- **Ambitious:** 60 GW. Estimated capacity that could be achieved with multiple ScotWind rounds and by going beyond current net-zero targets. This represents around 1/3 of the total practical developable Scottish offshore wind resource as estimated in 2010 by the Offshore Valuation Group.
- **Planned Development:** 30 GW. Aligned with Scotland delivering 40% of the 75 GW UK offshore wind deployment target recommended by the Committee on Climate Change.
- **Business as usual:** 27 GW. Continuing, but more conservative, deployment of offshore wind

Due to anticipated future grid constraints it was assumed, for purposes of this initial simplified analysis, that in all scenarios, the entire offshore wind would, or could, be used for hydrogen production. When then compared with the corresponding demand scenario, it can be seen that a considerable excess of green hydrogen is produced in all scenarios. This represents a valuable supply opportunity to the rest of UK and export opportunity to Europe where demand for hydrogen from the heating, transport and chemical feedstock sectors is growing. Indeed, due to grid constraints, green hydrogen may represent the best means to commercially develop the rich Scottish offshore wind resource in the longer term.

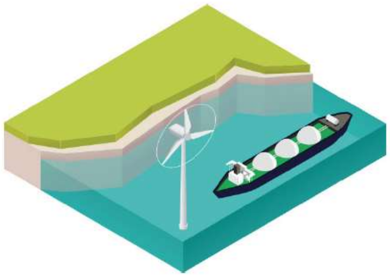


The primary export markets for Scottish green hydrogen are expected to be in Northern Europe (Germany, Netherlands & Belgium) which can be accessed by pipeline. Competition to supply these markets is expected come from hydrogen produced from solar energy in Southern Europe (notably Portugal) and North Africa.

Cost of Green Hydrogen Production

Levelised cost of hydrogen (LCoH) has been estimated for three base case production scenarios:

- Scenario 1: Small-scale pilot project for green hydrogen production from offshore wind;
- Scenario 2: Commercial scale offshore wind farm coupled with onshore hydrogen production;
- Scenario 3: Commercial scale offshore wind farm coupled with offshore hydrogen production.



Scenario 1 – Small-scale pilot project for green hydrogen production from offshore wind.

Scenario 2 – Commercial scale offshore wind farm coupled with onshore hydrogen production.

Scenario 3 – Commercial scale offshore wind farm coupled with offshore hydrogen production.

Result	Unit	Scenario 1	Scenario 2	Scenario 3
Year		2025	2028	2032
Wind Farm Capacity	MW	14	500	1000
Hydrogen Production	Te/day	3	119	276
LCoH	£/kg	6.2	2.9	2.3

- As expected, the results of the modelling show the cost of hydrogen production decreasing with reducing technology cost and increased scale. Xodus' analysis supports a long-term outlook of LCoH falling towards £2/kg for fixed bottom offshore wind turbines.
- Floating wind and any additional costs for transportation significantly increase the LCoH. The cost of hydrogen at the point of use must therefore take these logistics components into account on a case by case basis.
- Desalination cost and distance to shore do not significantly influence LCoH.

Cost Parity

The levelised cost of green hydrogen (LCoH) in 2032 has been compared with the parity price of equivalent hydrocarbon fuels both at the point of production of hydrogen and after including logistics cost for delivery. Further, where appropriate, fuel duty and VAT effects are shown. The analysis excluded any consideration of additional end user costs required for infrastructure (hydrogen fuelling stations, gas network upgrades), appliance retrofits or fuel cell vehicles, and therefore directly compares only fuel cost. There are currently still barriers to the widespread uptake of hydrogen solutions due to lack of conveniently available supply and limited or costly (particularly in the case of vehicles) consumer choices at this emergent stage of market adoption.

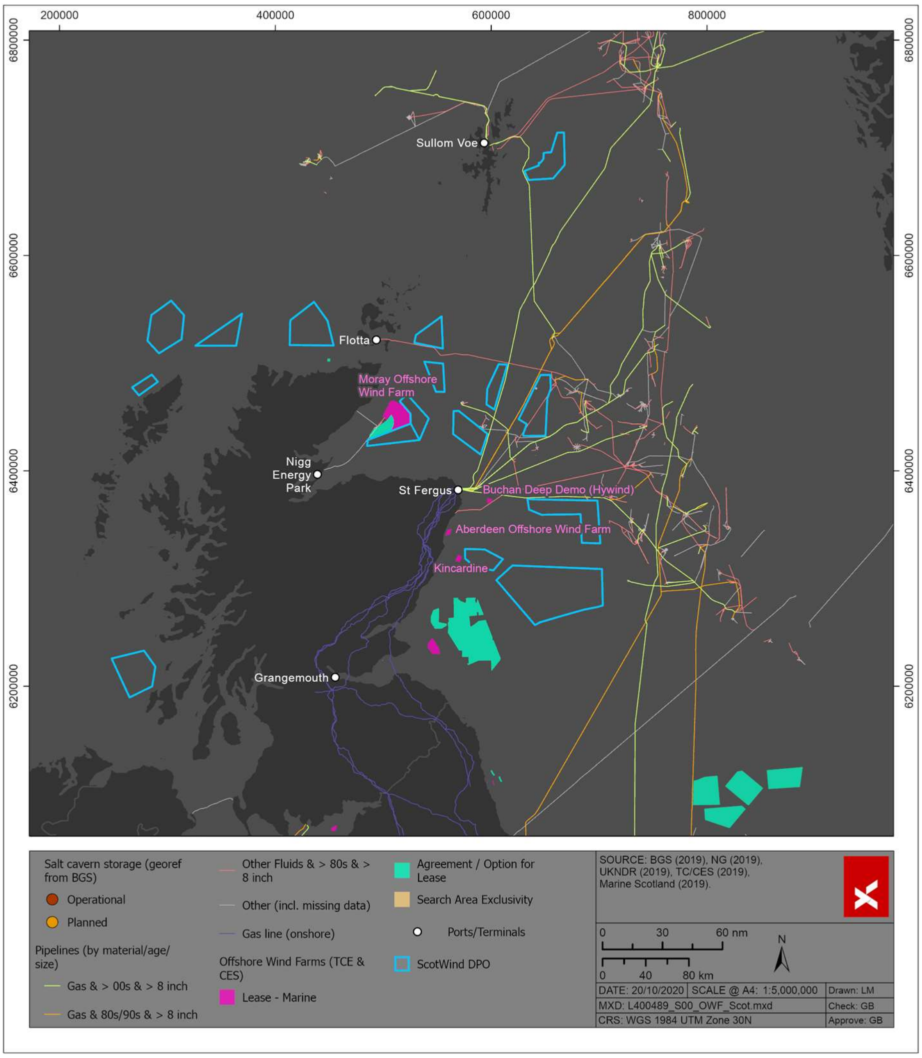
- Due to the existing taxation effects of fuel duty and VAT, untaxed hydrogen is shown to be cost-competitive with hydrocarbon fuel for cars and buses at the pump, without subsidy, where logistics costs (fuelling station, storage and transport cost) can be kept reasonably low (e.g. a centralised bus fleet).
- Projected green hydrogen production at £2/kg is equivalent to £50.8/MWh, higher than the £16.4/MWh natural gas commodity price equivalent. Direct substitution of natural gas by green hydrogen would therefore need to be supported by market intervention.
- In Scotland, the largest demand for hydrogen is expected to be for heat, replacing or (by blending) supplementing natural gas, where hydrogen can be delivered without substantial additional cost by using the existing natural gas network. The required support thus contrasts with minimal infrastructure investment needs.
- By contrast, significant investment would be required in offshore seasonal storage to enable hydrogen to replace natural gas as fuel for back-up electricity generation. Green hydrogen is not considered competitive in this sector, though the parity price assessment is more complex and not directly comparable with the other sectors illustrated.

Despite the vastly different cost parities to the end user, the fiscal support gap for hydrogen as a fuel substituting natural gas for heat or hydrogen mobility is within the margin of error. Individual hydrogen mobility is likely to require additional subsidies for costlier hydrogen vehicle acquisition.

Scottish Infrastructure

Scotland has a range of existing oil and gas infrastructure that could be repurposed to develop a hydrogen economy. This includes:

- An extensive infrastructure of existing O&G pipelines, much of which overlays the 2020 Offshore Wind Plan Option areas in the Sectoral Marine Plan, and includes four pipelines that currently connect the UK to continental Europe. Examples of repurposing exist but key challenges include long term integrity of now-aging pipelines, especially for the additional challenges of transporting hydrogen, and a potentially extended period between cessation of hydrocarbon production and repurposing for hydrogen transport.
- Several Scottish ports and terminals are well-equipped for hydrogen export and are already actively considering repurposing for hydrogen export.
- Depleted fields and other subsurface structures that would allow for large scale storage of hydrogen. Research in this area however is still in its infancy.

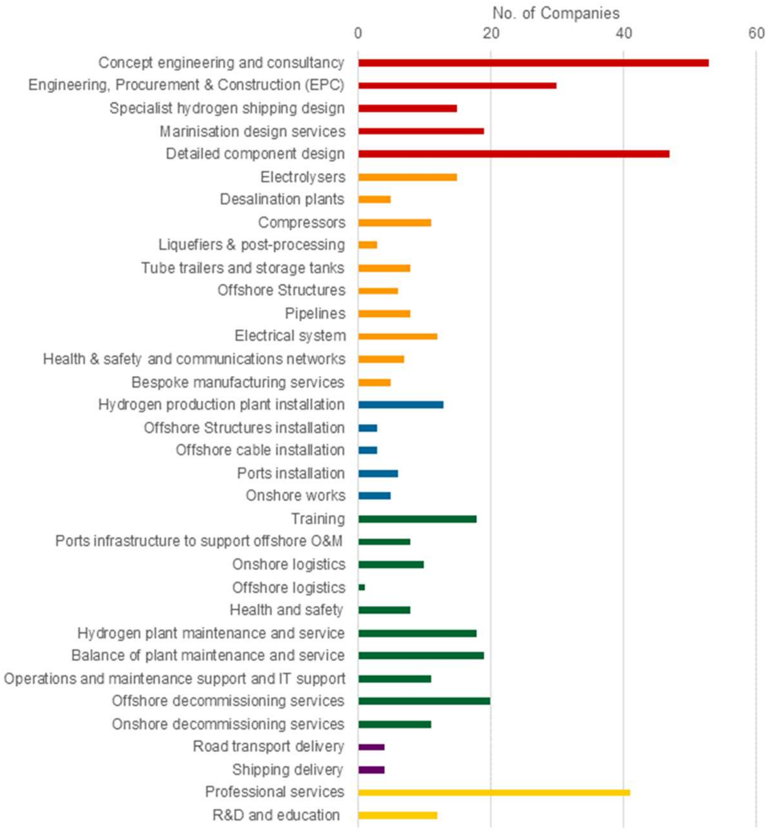


A co-ordinated strategy and plan for hydrogen transportation both within the UK and to Europe is required in order to maximise the efficient re-use of this existing infrastructure and to ensure optimum redevelopment of terminals and ports.

Supply Chain assessment

A database has been established of around 100 Scottish companies active in, or with an expressed interest in entering the green hydrogen sector.

- There is considerable hydrogen supply chain overlap with elements of parallel sectors, most notably, the oil and gas, offshore wind and subsea engineering sectors.
- The current strengths of the Scottish hydrogen supply chain are in the areas of project development, installation, Operations & Maintenance and sector support where these capabilities can be transferred from Scottish companies with experience in similar industries.
- Gaps in the Scottish supply chain are predominantly in supply areas bespoke to the design, manufacture and maintenance of hydrogen generation plant.
- Transportation of hydrogen appears to be an area with limited Scottish capability.
- The prevailing threat to the Scottish supply opportunity may be in a low pipeline of hydrogen generation projects.
- Established supply chains in competing markets may take advantage of low barriers to supplying Scottish projects or have stronger experience and track record than Scottish suppliers.
- Further work requires to be undertaken to address the skills gap, including retraining from oil and gas as well as potential apprenticeship opportunities, ensuring the Scottish workforce are ready to move quickly when required later this decade.



The Scottish supply chain is well positioned to support, and ultimately to benefit from, the development of green hydrogen. However, a steady pipeline of hydrogen developments over the next decade will be essential to ensuring the development of an indigenous supply chain so that Scotland is ready to deliver and take advantage of full commercial deployment.

1 INTRODUCTION

1.1 General

Wind power has already become a critical component of Scotland's electricity network, responsible for supplying 39.4% (18.9 TWh) of all electricity generated in the country in 2018, equivalent to 54.7% of Scotland's gross electricity demand (34.7 TWh). Onshore wind power has been particularly important source of new renewables capacity in recent decades, representing more than 80% (6.2 GW) of the 7.7 GW of renewables generation deployed in Scotland over the period 2009 to 2018.

Offshore wind is also emerging as an important source of future power generation for Scotland, offering the potential for very large-scale deployment at an increasingly competitive £/MWh price point. Scotland's current offshore wind generation capacity (894 MW) is much smaller than its onshore wind capacity (8,357 MW), but the nation has a significant pipeline of around 7.5 GW of projects under construction, with offshore consent, or with a seabed lease. This pipeline is set to grow substantially following the completion of the first ScotWind Leasing round, which will enable up to 10 GW of new offshore wind capacity via award of Option Agreements for project development.

Onshore and offshore wind will be vitally important for the ongoing decarbonisation of the Scottish and UK power network, as reflected by the UK Government's commitment to support both technologies via future Contracts for Difference (CfD) auction rounds – the government's main mechanism for supporting low-carbon electricity generation. The extensive UK offshore wind resource also offers considerable potential to support decarbonisation of other facets of the UK energy system via increased electrification and/or the displacement of existing fossil fuel-based systems with hydrogen alternatives fuelled by green hydrogen produced from offshore wind. It should be noted that although this report focuses solely on offshore wind, Scotland could also harness its significant marine renewables resources (waves and tidal) for green hydrogen production in the future.

The route to market for offshore wind projects supplying electricity to the grid is already well established. However, there is growing interest from industry and policymakers in exploring and enabling routes to market for the large-scale production of hydrogen from offshore wind, including for potential export. This opportunity was highlighted by the recent Offshore Renewable Energy Catapult (OREC) 'Offshore Wind and Hydrogen: Solving the Integration Challenge' report, which estimated that up to 240GW of offshore wind could be deployed in the UK by 2050 for the purpose of producing green hydrogen for export to Europe.

The green hydrogen export opportunity is also evident in the recently released German National Hydrogen Strategy (German Federal Government, 2020), which states that "around 90 to 110 TWh of hydrogen will be needed by 2030" and outlines plans for "up to 5GW of [domestic] electrolyser generation capacity including the offshore and onshore energy generation facilities" to help meet this demand. The strategy notes, however, that "most of the hydrogen needed will have to be imported", describing "several places across the EU where large quantities of renewables-based electricity are being generated" as offering great potential to meet this demand. Considering that Scotland is already a net exporter of renewable power indicates that it could also become an exporter of green hydrogen in the future to the rest of the UK and other energy markets, such as Germany.

1.2 Wind to Green Hydrogen Overview

The current forecast from the UK Committee on Climate Change (Committee on Climate Change, 2018) for global low-carbon hydrogen demand in 2030 varies between 35-1,100 TWh/year, scaling up to 300-19,000 TWh/year by 2050. Considering that more than 95% of global hydrogen supply is currently produced from fossil fuels (2,800 TWh/year (IEA, 2019) the opportunity for zero-carbon hydrogen produced by large-scale electrolyser systems is enormous.

Scotland is one of the leading nations in green hydrogen, having developed the world's first hydrogen production system from tidal energy (Surf'n'Turf, 2017), incorporating anaerobic digestion (AD), combined heat and power (CHP) and electrolysis to produce and utilise hydrogen and oxygen as part of the Outer Hebrides Local Energy Hub (OHLEH). These are examples of multiple pioneering Scottish hydrogen projects, which also include the world's first hydrogen-powered double decker bus fleet in Aberdeen. With increasing domestic and international demand for hydrogen, offshore wind coupled with electrolysis presents a green solution with potential to address large scale demand. Scotland has a growing offshore wind sector, but with increased requirements for grid infrastructure upgrades and curtailment risk, hydrogen production could act as an alternative revenue stream to support continued offshore wind development, whilst serving to decarbonise 'difficult-to-abate' sectors.

Figure 1.1 shows key components of Scotland's potential future hydrogen system.

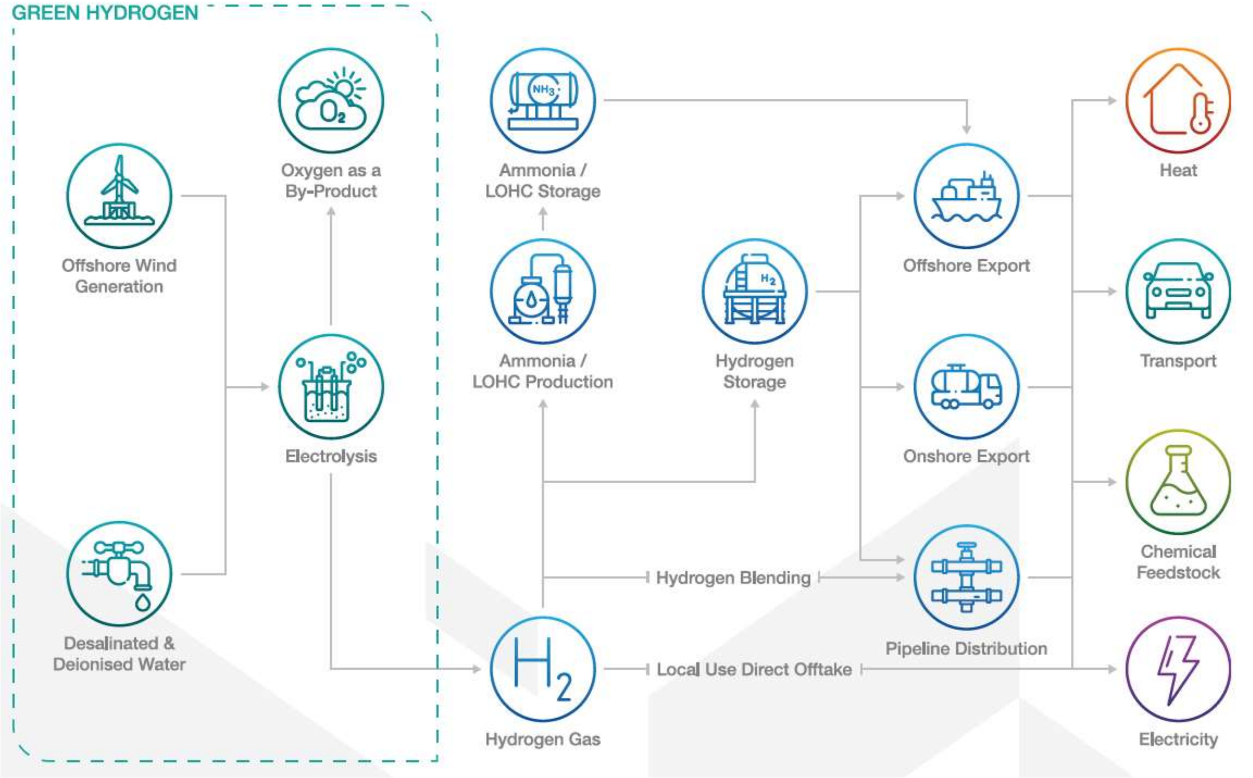


Figure 1.1. Hydrogen economy based on offshore wind generation

1.3 Project Scope

This study was a multifaceted assessment of the Scottish opportunity to produce green hydrogen from offshore wind.

The key components of the scope of work were as follows:

- To asses existing and potential demand for green hydrogen in Scotland, and to explore how this demand is likely to change and evolve over a timeframe to 2045.
- To examine the markets that represent the greatest opportunity for Scottish green hydrogen, and identify key demand hubs in continental Europe.
- To provide clear understanding of the Scottish offshore wind resource coupled with green hydrogen production, and how these two clean technologies can enable green hydrogen production at scale.

- To deliver a granular supply chain database of Scotland based companies with existing or potential capabilities which will be crucial to decarbonise carbon intensive sectors not only in Scotland, but also abroad by exporting surplus hydrogen to Europe. . NB the scope of this study excluded consideration of potential for Scottish export of hydrogen sector goods and services.
- To build a techno-economic model to calculate hydrogen production from offshore wind.
- To outline key policy incentives to make hydrogen cost competitive with other dispatchable energy sources (fossil fuels).

1.4 Work Package Overview

The scope of work was split into three primary work packages, addressing three key themes:

- **Market Demand**. The potential market demand for hydrogen within Scotland, the rest of the UK and Europe and how these might develop up to 2045. What consumer parity prices might be now, and in 2032 once the energy transition is well-underway. The scope comprised:
    - Undertaking an extensive desk-based review of relevant reports and policy documents, both Scotland-specific and international.
    - Using this information to understand the scale of demand market for green hydrogen between the late 2020s and 2045/50.
- **Scotland's Potential.** What scale of production of green hydrogen might be obtained from Scotland's offshore wind resource, and how this might develop up to 2045. The maturity of Scotland's supply chain capability to deliver green hydrogen. How Scotland's extensive existing oil and gas infrastructure might be redeployed to facilitate production of green hydrogen. The scope comprised:
    - Defining the current green hydrogen landscape in Scotland.
    - Identifying and engage with key industry stakeholders to create a robust supply chain database of Scottish businesses that are already active or considering entering the green hydrogen sector.
    - Assessing the Scottish supply chain opportunity and identify the actions to be taken that will maximise the potential benefits.
- **Production Models**. What cost and LCOH may be expected for various potential project configurations and, based on these, what interventions and mechanisms may be needed to enable the development of a green hydrogen economy. The scope comprised:
    - Creating a techno-economic model to identify and evaluate the key economic metrics of hydrogen production from offshore wind.
    - Using this model to understand the scale of potential incentives required for green hydrogen to compete with the current use of fossil fuels.
    - Using these findings to identify future policy mechanisms to achieve wider economic, social and environmental benefits of hydrogen economy in Scotland.

1.5 Abbreviations

Abbreviation	Explanation
AD	Anaerobic Digestion
BBL	Balgzand Bacton (pipe)Line
bcm	Billion cubic metres
BEIS	Department for Business, Energy & Industrial Strategy (UK Government)
BEV	Battery Electric Vehicle
BSUoS	Balancing Services Use of System (charge)
CO_2	Carbon Dioxide
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Use and Storage
CfD	Contract for Difference
CHP	Combined Heat and Power
CnES	Comhairle nan Eilean Siar
DECEX	Decommissioning Expenditure
DEVEX	Development Expenditure (pre-FID)
EMEC	European Marine Energy Centre
EU	European Union
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
FCHJU	Fuel Cells and Hydrogen Joint Undertaking
FRP	Fibre Reinforced Plastic
GW	Gigawatt
GWh	Gigawatt Hour
H2	Hydrogen (strictly H_2)
HHV	Higher Heating Value
HIE	Highlands & Islands Enterprise
HMRC	Her Majesty's Revenue and Customs
HPA	Hydrogen Purchase Agreement
IEA	International Energy Agency
in	inch
IRENA	The International Renewable Energy Agency
IUK	Interconnector UK
kg	kilogram

km	kilometre
LCO	Low Carbon Obligation
LCoE	Levelised Cost of Energy
LCoH	Levelised Cost of Hydrogen
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LOA	Length Overall (ship)
LOHC	Liquid Organic Hydrogen Carrier
MGO	Marine Gas Oil
mpg	miles per gallon
MW	Megawatt
MWh	Megawatt hour
NECCUS	North East CCUS
NH3	Ammonia
NPD	Norwegian Petroleum Directorate
NPF	National Performance Framework
NPV	Net Present Value
NTS	National Transmission Service (gas network)
O&G	Oil and Gas
O&M	Operations and maintenance
OFTO	Offshore Transmission Owner
OGTC	Oil and Gas Technology Centre
OHLEH	Outer Hebrides Local Energy Hub
ONE	Opportunity North East
OPEX	Operating Expenditure
OREC	Offshore Renewable Energy Catapult
OWF	Offshore Wind Farm
PEM	Polymer Electrolyte Membrane (electrolyser)
POX	Partial Oxidation
PPA	Power Purchase Agreement
RFTO	Renewable Transport Fuel Obligation
ROC	Renewable Obligation Certificates
SE	Scottish Enterprise
SG	Scottish Government
SGN	Scottish Gas Networks

SHA	Scottish Hydrogen Assessment (study)
SHFCA	Scottish Hydrogen & Fuel Cell Association
SMR	Steam Methane Reforming
SWOT	Strengths, Weaknesses, Opportunities, Threats
TNEI	The Northern Energy Initiative
TNUoS	Transmission Network Use of System (charge)
TWh	Terrawatt Hour
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
US	United States
VAT	Value-Added Tax
VLGC	Very Large Gas Carrier
WLTP	Worldwide Harmonised Light Vehicle Test
WP	Work Package

1.6 Unit Conversion Tables

1.6.1 Hydrogen

Scale	Unit of Measurements		
	Energy	Volume	Weight
Annual Cumulative Flow	1 TWh	12.6 BCF	0.03 Mte
Daily Flow	1 GW	302.4 MMSCFD	717.5 Te/d

1.6.2 Ammonia

Scale	Unit of Measurements		
	Energy	Volume	Weight
Annual Cumulative Flow	1 TWh	7.9 BCF	0.16 Mte
Daily Flow	1 GW	190.2 MMSCFD	3,840 Te/d

2 MARKET DEMAND FOR GREEN HYDROGEN

2.1 Introduction

This section assesses the market demand for green hydrogen and its target cost to compete with conventional fossil fuels. The assessment considers Scotland's existing users and infrastructure, as well as academic, and research and development expertise. These combined with Scotland's geographical capabilities, including energy-intensive industrial hubs, help to identify current and emerging energy demand to displace existing, fossil-fuel derived feedstocks with green hydrogen.

The aim was to model the overall future energy demand in Scotland and identify the most relevant hydrogen hubs within the country, rather than mapping individual areas. Three scenarios were developed that showed different sizes of hydrogen economy in Scotland. These scenarios were derived from the Scottish Hydrogen Assessment (SHA) (Arup, 2020), which developed a range of distinct viable scenarios for hydrogen deployment in Scotland and provided an economic assessment of those scenarios.

The following scenarios with corresponding roadmaps were created:

- **Ambitious**: Full transition towards a hydrogen economy in Scotland, based on the most optimistic assumptions.
- **Planned Development**: Optimistic scenario based on a wide hydrogen technology deployment and use across all sectors.
- **Business as Usual**: Conservative scenario with modest hydrogen use and extensive electrification.

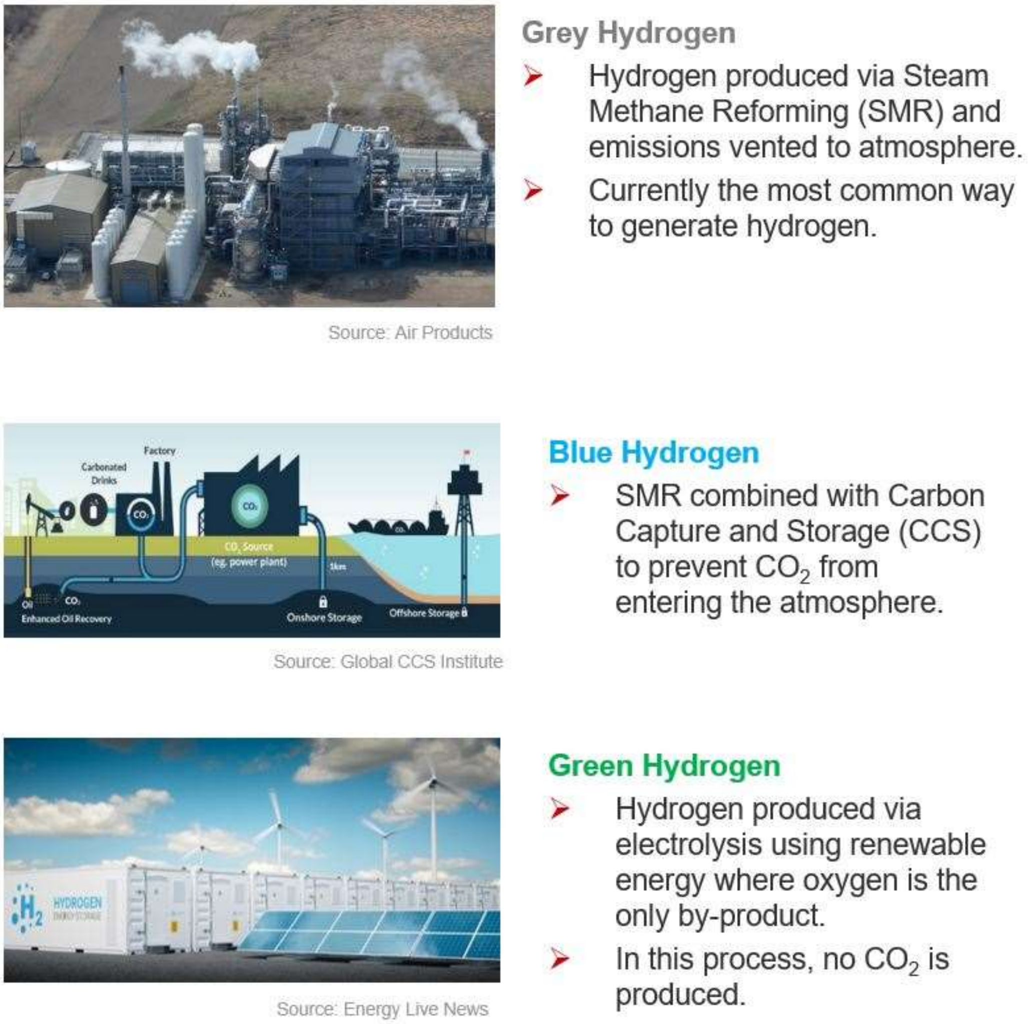
Each scenario outlined how demand in Scotland is likely to change and evolve over a timeframe from present day to 2045, with focus on 2025 and 2032. The assessment considered different sectors that are likely to enter the green hydrogen sector and outlined how demand may vary between 2025 and 2045 based on the SHA. This was an important step to understand the impacts that green hydrogen may have on both national and local economies. The established high-level hydrogen demand was directly linked to specific markets that represent the greatest opportunity for Scottish green hydrogen which would allow transition towards the net-zero target by 2045.

The study focused on the cost that consumers would be willing to pay to replace the use of currently used fossil fuels. We demonstrate the predicted price of what fossil fuels will be in future years and therefore what the price of hydrogen needs to be for end-users. It does not focus on establishing the actual full costs of hydrogen production and corresponding sale price. These cost parity projections were crucial for further calculations to establish the potential gap between green hydrogen production cost and the hydrogen market price. Hydrogen can replace various fossil fuel sources across different sectors, which means that the end-user market price will vary significantly across the demand sectors. These markets were assessed independently to establish the corresponding market prices.

Finally, this section also identifies hydrogen demand hubs across Europe and assess what the cost parity may be in these regions to outline where Scotland's green hydrogen could be best exported to in the future.

2.2 Hydrogen Demand Assessment

This section focuses on assessing Scotland's future hydrogen demand, whilst identifying key links with other countries and regions. Although this study is dedicated solely to green hydrogen, it should be highlighted that there are other ways to produce hydrogen apart from electrolysis as shown in Figure 2.1



Grey Hydrogen

- Hydrogen produced via Steam Methane Reforming (SMR) and emissions vented to atmosphere.
- Currently the most common way to generate hydrogen.

Source: Air Products

Blue Hydrogen

- SMR combined with Carbon Capture and Storage (CCS) to prevent CO_2 from entering the atmosphere.

Source: Global CCS Institute

Green Hydrogen

- Hydrogen produced via electrolysis using renewable energy where oxygen is the only by-product.
- In this process, no CO_2 is produced.

Source: Energy Live News

Figure 2.1. Hydrogen type based on production processes

2.2.1 Worldwide Hydrogen Demand

Current global hydrogen production is around 70 million tonnes (energy equivalent of 2,800 TWh)[1] per year (IEA, 2020), with the UK producing approximately 1% of the global production (27 TWh) (Committee on Climate Change, 2018)[2]. In 2018, the primary source for dedicated hydrogen production came from natural gas through steam methane reforming - 71%, coal through gasification - 27%, and the remaining 2% from partial oxidation of oil and electrolysis (see Figure 2.2) (IEA, 2019). Hydrogen is also produced as a by-product from chemical processes, which predominantly use oil as a primary feedstock. Only electrolysis delivers a zero-carbon fuel, whereas the other methods of hydrogen production are all carbon emitting.

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[1] For unit conversion between kg and MWh, the report is using energy density of hydrogen based on Higher Heating Value (HHV) of 141.9 MJ/kg (39.4 kWh/kg) to reflect the most end-use agnostic estimates (e.g. ammonia or refining sectors can use hydrogen directly).

[2] To gain a better understanding of the scale, the UK overall energy consumption in 2018 was 1,663 TWh.

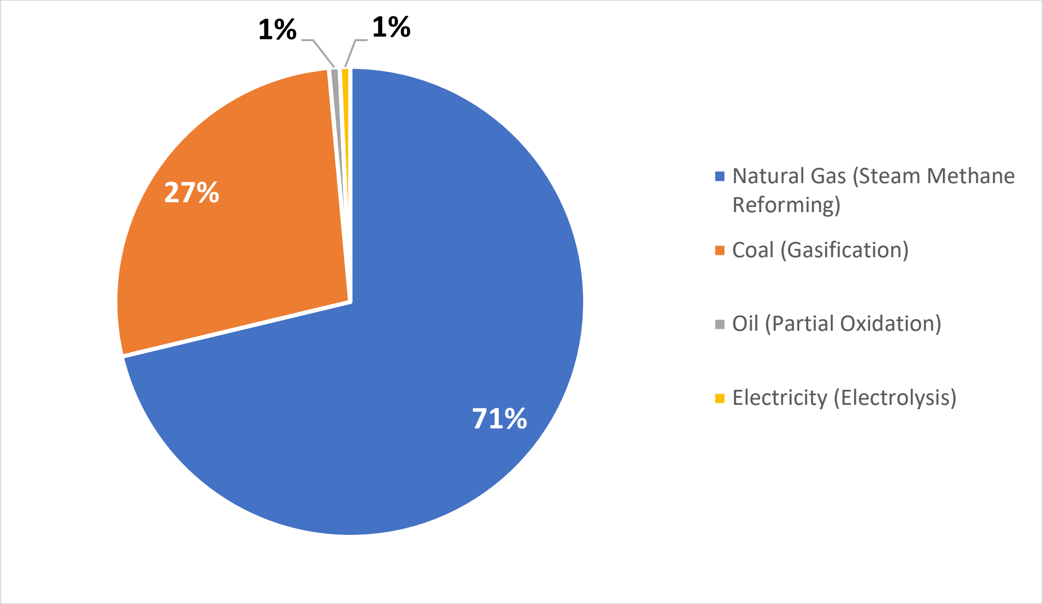

Figure 2.2. Primary source for global dedicated hydrogen production in 2018 (IEA, 2019)[3]

Hydrogen is widely used within industrial processes worldwide, predominantly for petroleum refining and recovery (46%) and ammonia production (44%) (Committee on Climate Change, 2018). These two sectors combined consume more than 90% of global pure hydrogen supply. Therefore, have the highest impact on the global pure hydrogen trade.

Global demand for hydrogen continues to rise. It has increased more than 3 times since 1975 as shown in Figure 2.3[4]. It currently accounts for 6% of global natural gas and 2% of coal worldwide. This leads to a significant carbon dioxide (CO_2) footprint, which accounted for 830 million tonnes of CO_2 in 2019 (IEA, 2019), almost twice as much as the overall CO_2 emissions of the UK (BEIS, 2020).

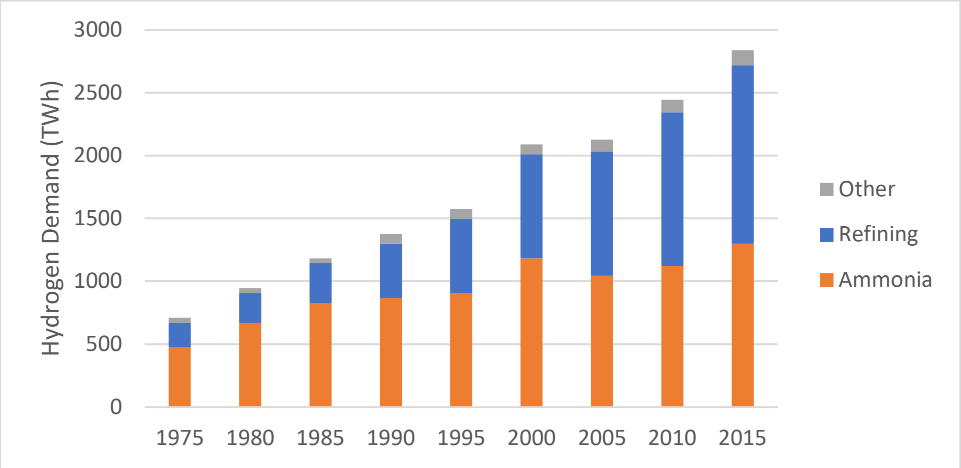

Figure 2.3. Global demand for pure hydrogen (IEA, 2019)

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[3] Figure 1.1 only includes **dedicated** hydrogen production without hydrogen produced as a by-product.

[4] Figure 2.3 only includes demand for **pure** hydrogen without hydrogen mixed with other gases.

Although global demand for pure hydrogen has been slowly rising for the past decades (mainly due to the increase demand for refining and ammonia used for agricultural purposes), most projections suggest that it will grow significantly faster in the coming years. BloombergNEF projects that hydrogen demand will grow 3-22x between 2020 and 2050, depending mainly on policy support across the globe (BloombergNEF, 2020).

The projected increase across various demand sectors is particularly evident in ‘difficult-to-decarbonise’ sectors, which have very few alternative low-carbon options to meet the net-zero targets. These sectors include heavy duty transport, shipping, aviation, high-grade heat used for industry or large-scale, long-term storage of renewable electricity generation. Figure 2.4 shows an example of global hydrogen demand projection between 2019 and 2070 (IEA, 2020)[5].

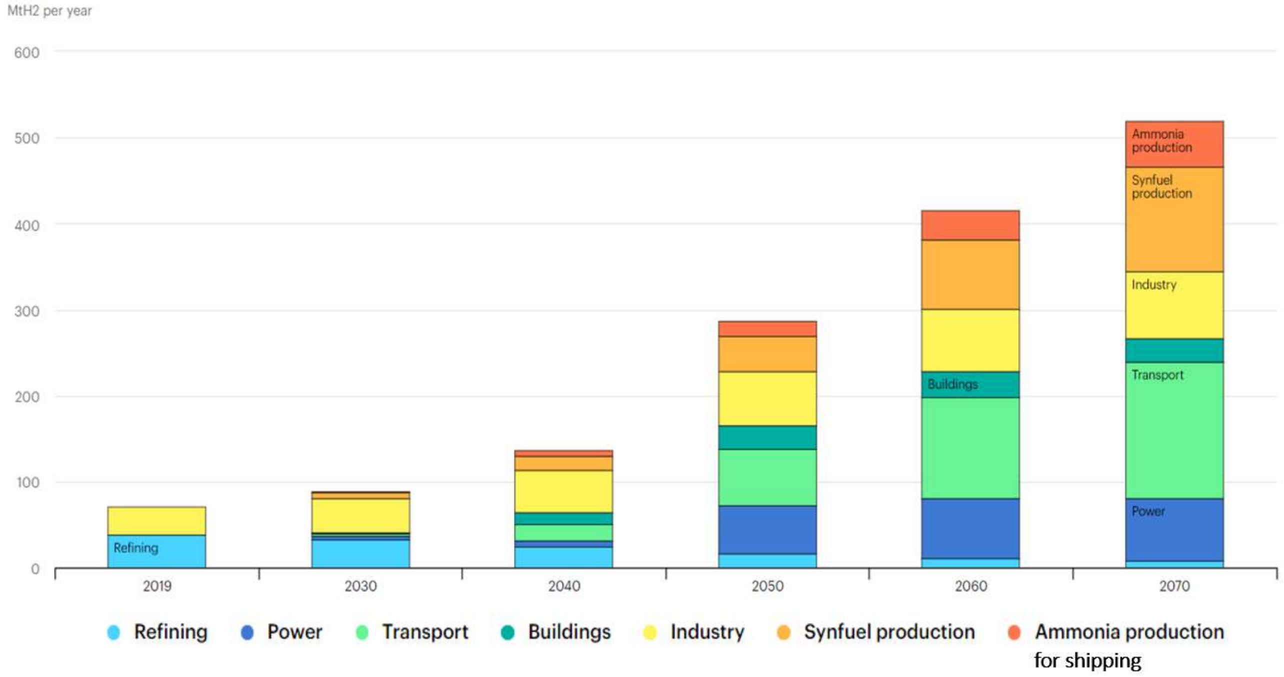

Figure 2.4. Global hydrogen demand projections (IEA, 2020)

2.2.2 Hydrogen Demand in Europe and the UK

Although hydrogen can be used as an energy vector to decarbonise the majority of energy sectors, some sectors are more likely to adopt hydrogen technologies than others as shown in Figure 2.5. The figure shows the key sectors that could most benefit from the adoption of hydrogen technology and includes the anticipated timeframes for these solutions to be able to be deployed on a large-scale. Hydrogen use within sectors like power generation or low and medium grade industrial heat are expected to face stronger competition from other low-carbon alternatives. On the other hand, heating in buildings, ammonia production and refining could become the largest sectors in the hydrogen economy between 2020 and 2035. Sectors such as high-grade heat, aviation or shipping are also likely to rely significantly on hydrogen supply, although this is likely to be further into the future, 2035-2050. This is because zero-carbon hydrogen is one of the only solutions to decarbonising these energy intensive sectors (FCH JU, 2019) (OREC, 2020).

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[5] Ammonia production refers to the fuel production for the shipping sector. Hydrogen use for industrial ammonia production is included within the industry use.

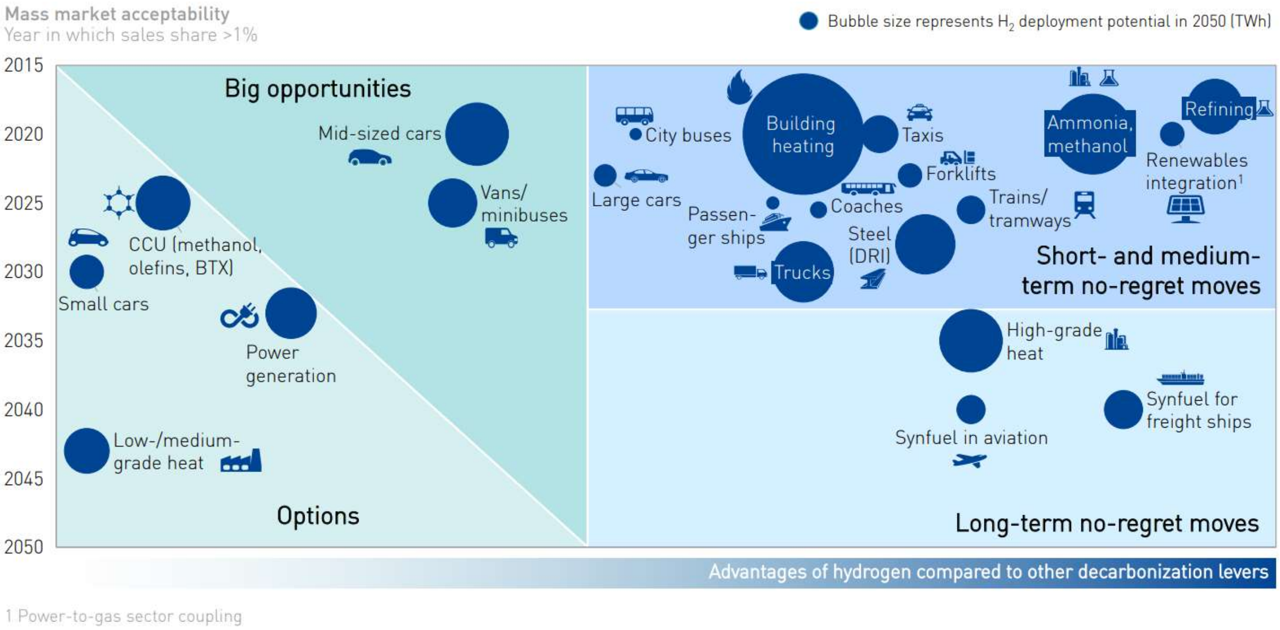

Figure 2.5. Energy sectors that can benefit from a wide deployment of hydrogen technology (FCH JU, 2019)

The disparity between certain parts of the world with abundant, low-cost energy sources (both natural gas and renewable electricity) and other regions with higher hydrogen demand could result in an international hydrogen trade development.

The European Union (EU) Fuel Cells and Hydrogen Joint Undertaking (FCH JU) initiative estimates that hydrogen could supply up to 24% (2,250 TWh) of total energy demand by 2050 if the 2-degree target is to be met, around 85% of the current global hydrogen production. This is equivalent to fuelling 42 million large cars, 1.7 million trucks, 250,000 buses, and more than 5,500 trains[6] (FCH JU, 2019). Two key scenarios representing rapid uptake of hydrogen technologies by 2050 compared to a business-as-usual scenario are shown in Figure 2.6

The figure shows that transport and heat are the two key sectors to be decarbonised with hydrogen technology. Industry is also likely to use hydrogen as the main driver, whereas power generation represents the lowest need for hydrogen technology. Renewable power generation is rather the key enabler of green hydrogen production through electrolysis.

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[6] This statement indicates the scale of opportunity rather than making future projections within each sector.

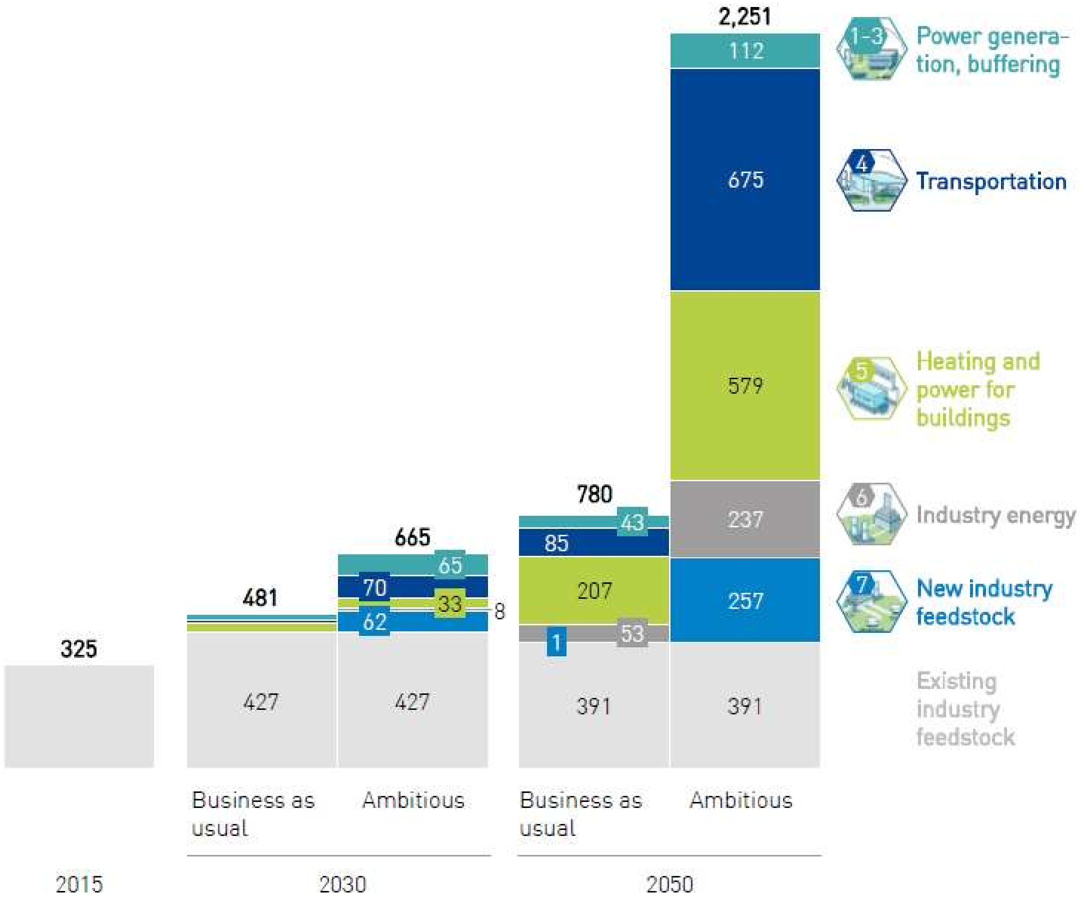

Figure 2.6. EU hydrogen uptake scenarios in 2030 and 2050 in TWh (FCH JU, 2019)

Future hydrogen demand projections for the EU vary greatly depending on each scenario. In the business-as-usual scenario, hydrogen will have insignificant importance on the overall energy mix. In the high-grade heat segment, it would gain a maximum market share of 7% in 2050, equivalent to 50 TWh of hydrogen demand. On the other hand, the ambitious scenario estimates that hydrogen will be used across all energy sectors, particularly for transportation, heating and power for buildings, and industry.

Sectors that will rely on fuel cells, such as transportation, will require hydrogen with high purities. Green hydrogen produced through electrolysis can meet the purity criteria. Hydrogen produced through other methods, such as SMR, will require additional processes to reach the required purity levels. It should be noted that this requirement does not apply to sectors where hydrogen is being burnt, such as the heat sector.

FCH JU predicts that no new SMR plants will be built after 2030 as electrolysis will become the cheapest way to produce hydrogen through economies of scale. Furthermore, all existing SMR plants will be gradually retrofitted with CCS to make the processes carbon neutral and further increase the price of hydrogen from natural gas (FCH JU, 2019). These scenarios demonstrate that although the actual volume of hydrogen required by 2030 and 2050 is uncertain, currently produced grey hydrogen will be replaced with electrolysis and CCS enabled SMR facilities.

One of the largest hydrogen sectors in Europe is likely to be heating, with hydrogen blending[7] already being pursued in countries such as Germany, France, the Netherlands and the UK. Pilot projects underway include:

- H100 Fife project in Scotland is aiming to use 100% hydrogen to heat 300 local homes in Levenmouth - a five-year fully operational phase is planned from 2022/2023 (SGN, 2020).
- The HyDeploy project in Germany (HyDeploy, 2020) and GRHYD project (Engie, 2020) in France which are both testing blending of up to 20% hydrogen
- Leeds is planning to be supplied with 100% hydrogen by 2028 through the H21 Leeds City Gate project (H21, 2020).

These frontrunners in blending or injecting pure hydrogen into the gas grid are likely to drive further uptake of hydrogen technology throughout Europe (FCH JU, 2019). Countries with the highest potential for hydrogen use in the heating sector as determined by FCH JU are shown in Figure 2.7. Based on the total energy demand and the percentages of natural gas share and the heating and cooling share, countries with the highest potential for replacing natural has with hydrogen are Germany, Italy, the Netherlands, UK and France.

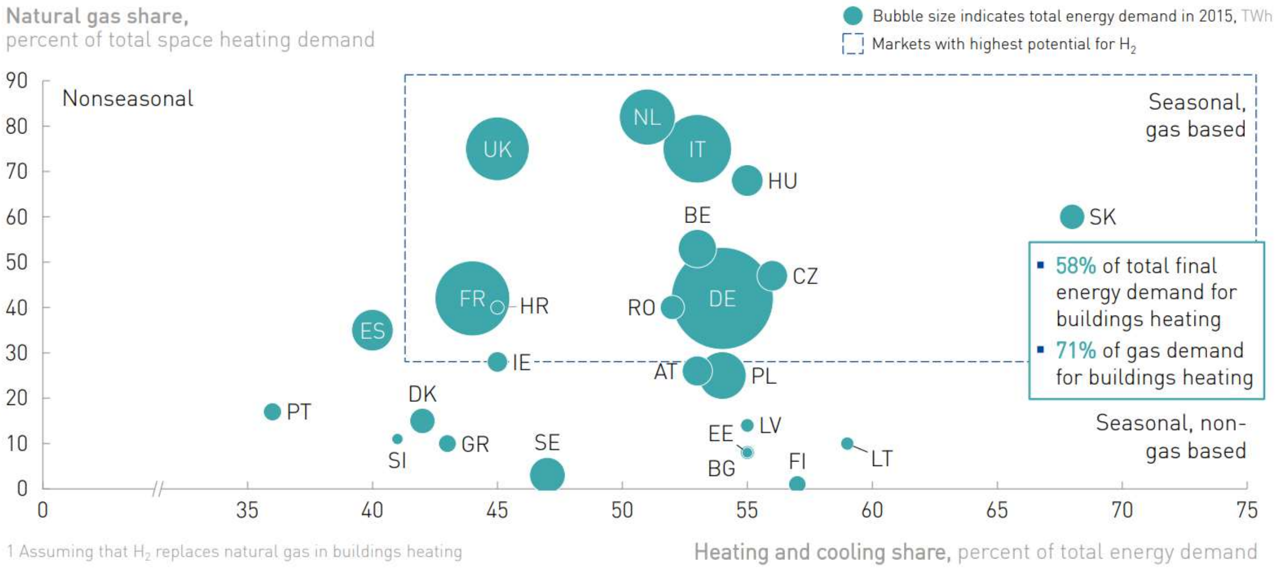

Figure 2.7. European markets with the highest potential for H_2 (FCH JU, 2019)

Large-scale, low-carbon hydrogen production projects have also been advancing recently, which will be crucial to meet Europe's hydrogen demand in line with the 2-degree target. Several major demonstration projects are underway. The first wind-to-hydrogen pilot sites are in operation or in construction across Europe, e.g., in Germany, UK, Italy, Spain, the Netherlands, Denmark, and in the North Sea for offshore wind (FCH JU, 2019).

A 100 MW power-to-gas plant known as Hybridge for sector coupling[8] is planned to be deployed in Germany in 2023 (Wind Power Monthly, 2019). Hybridge will produce green hydrogen using renewable solar and wind power to electrolyse water. The Hydrogen Valley project in Northern Netherlands is a new pilot scheme funded

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[7] *Hydrogen blending* is a process where low-carbon hydrogen is mixed with natural gas in the gas pipeline network to lower the carbon intensity of the end-product.

[8] *Sector coupling* means integrating various supply and demand sectors into a whole-system network to increase the overall efficiency and cost-effectiveness.

through the FCH JU initiative, expecting to further develop hydrogen technology together with Northern Germany (Hyer, 2019) (see Figure 2.8).

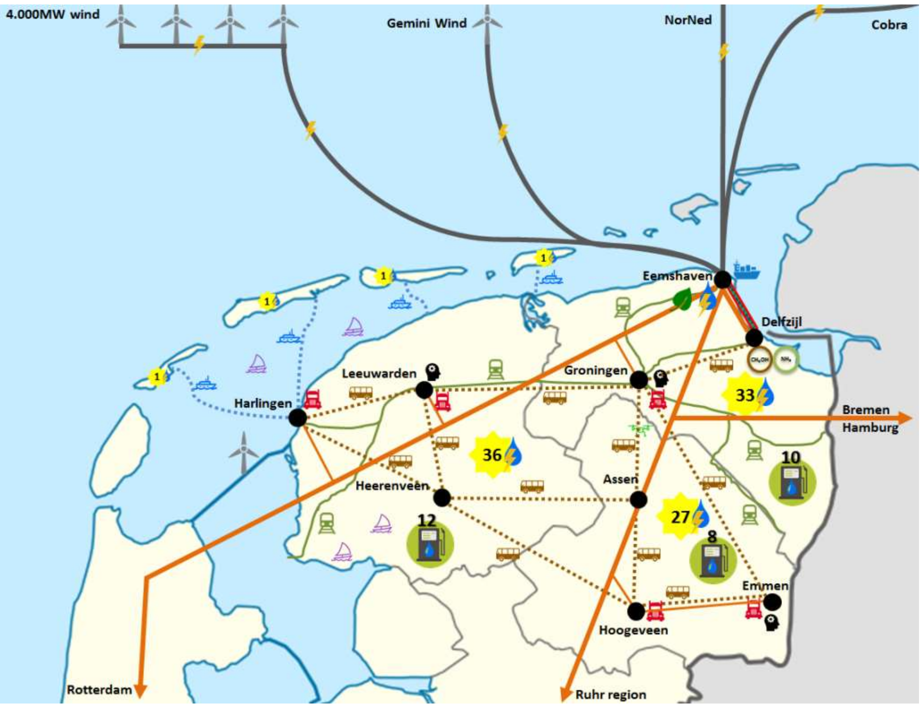

Figure 2.8. Hydrogen Valley project (FCH, Hydrogen Valley, 2019)

There is also the North Sea Wind Power Hub project (see Figure 2.9), which focusses on connecting 10,000 offshore wind turbines in the North Sea to a centralised artificial island. The project will enable a large-scale power-to-hydrogen production and is currently planned to be built after 2030 (FCH JU, 2019). The consortium currently includes the Netherlands, Germany and Denmark. Potential future member countries are UK, Norway and Belgium.

Figure 2.9. North Sea Wind Power Hub project (4C Offshore, 2017)

2.2.3 Scotland’s Hydrogen Demand Projections

This section includes the assessment of Scotland’s market demand for hydrogen between 2025 and 2045. Since the aim of this study was predominantly focused on the supply (upstream) and transport (midstream) of hydrogen, the hydrogen demand scenarios are aligned with the SHA.

It should be noted that hydrogen export is excluded from this initial assessment - it is focused on hydrogen demand in Scotland only. Any surplus from the hydrogen production scenarios considered in Chapter 4 will then be considered as ‘potential export’.

The three scenarios used in this report are as follows;

> **Ambitious**: Full transition towards a hydrogen economy in Scotland. This scenario is based on a combination of the most ambitious projections for each sector from the SHA.

> **Planned Development**: Optimistic scenario based on wide-ranging hydrogen technology deployment and use across various sectors. This scenario was aligned with *Scenario A: ‘Hydrogen Economy’* from the SHA.

> **Business as Usual**: Conservative scenario with modest hydrogen use and extensive electrification across all sectors. This scenario was aligned with *Scenario C: ‘Focused Hydrogen’* from the SHA.

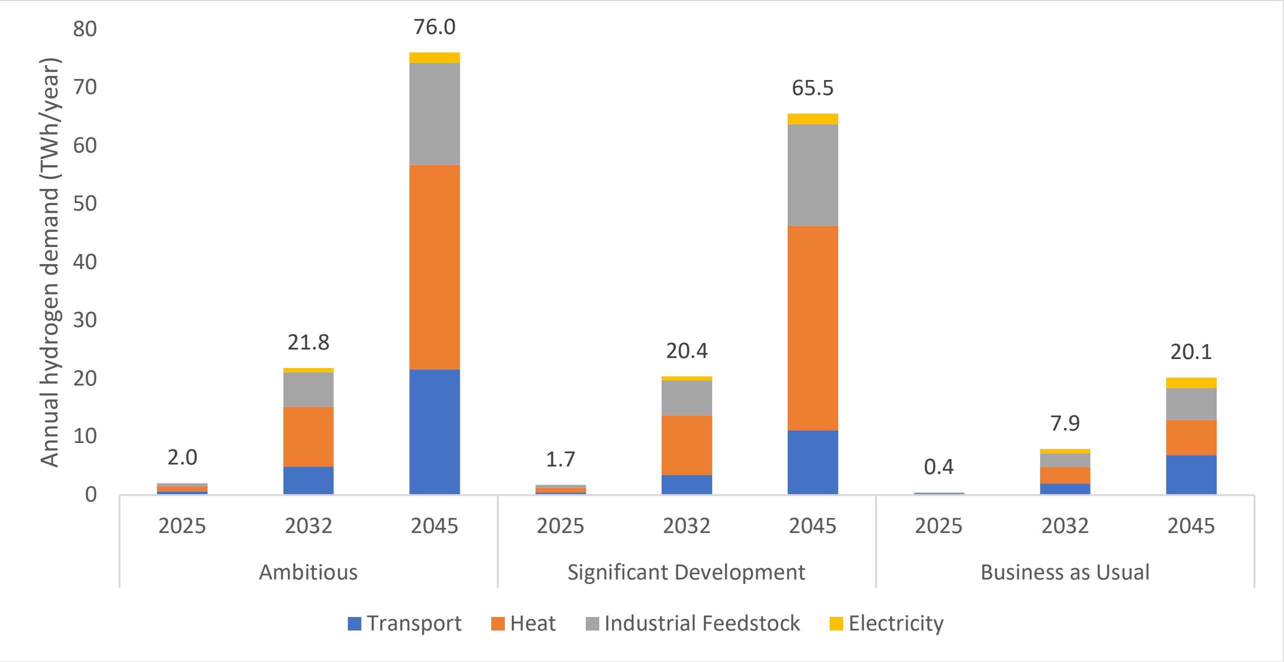

Figure 2.10. Scotland’s Hydrogen Demand Projections

Ambitious Scenario

The ambitious scenario focuses on Scotland's hydrogen demand in 2025, 2032 and 2045, if Scotland's hydrogen demand technologies were to be fully deployed across all energy sectors. This scenario was created by combining the most optimistic assumptions in each sector stated in the SHA.

2025

In 2025, hydrogen use across all sectors is relatively limited even in the ambitious scenario. There is modest uptake of hydrogen technologies within heat (0.9 TWh), transport (0.6 TWh), and industrial feedstock sectors (0.5 TWh), but none in the electricity sector.

Hydrogen in the transport sector is used predominantly in the public sector organisations – buses or council fleets. There are also some demonstration projects focused on hydrogen trains and ferries. Other demonstration projects include heat and industrial feedstock sectors. However, these are rather co-located projects (hydrogen is produced near the demand side, which results in a co-location of supply and demand) spread across Scotland (such as the H100 heating project in Fife), rather than a widespread hydrogen blending in the entire of Scotland. Even in this optimistic scenario, hydrogen only meets 1-2% of Scotland's overall energy demand.

2032

By 2032, hydrogen technology undertakes a significant step from being a minor clean energy vector to become a key player in decarbonisation efforts. The heat sector especially has adopted green hydrogen as a viable clean energy source replacing natural gas within the national grid (up to 20% in the overall network and 100% in some isolated trial projects).

There is more than 10 TWh hydrogen used annually in the heat sector, almost 6 TWh of hydrogen used as industrial feedstock and nearly 5 TWh for transport. Hydrogen is also used as a back-up source within the power generation peaking plants[9] sector (more than 0.7 TWh). Hydrogen meets less than 15% of Scotland overall energy demand in 2032.

2045

By 2045, Scotland meets the net-zero target with hydrogen being at the core of this green energy transition. Scotland's gas network has been fully converted for hydrogen use. Hydrogen has become the main commercial and domestic heating fuel (35 TWh), accounting for nearly half of the overall annual hydrogen demand in Scotland. Hydrogen is also extensively used as industrial feedstock (17.5 TWh).

Nearly all petrol and diesel vehicles have been replaced by hydrogen fuel cell or battery electric vehicles. Hydrogen is particularly popular within aviation, shipping and larger vehicles, whereas EVs target the smaller domestic vehicle market. Hydrogen accounts for more than 21.5 TWh within Scotland's transport sector in 2045. Peaking plants have also increased their capacities to nearly 1.8 TWh. Hydrogen is widely used within Scotland's distillery sector as well as heavy industries requiring high-grade heat. The overall annual hydrogen demand in Scotland is 76 TWh, around half of Scotland's total energy demand.

Planned Development Scenario

The planned development scenario focuses on Scotland's hydrogen demand in 2025, 2032 and 2045, assuming optimistic projections with regards to hydrogen technology uptake. This scenario was created by using the inputs from Scenario A within the SHA, called 'Hydrogen Economy', which is the most ambitious scenario within the SHA (when excluding hydrogen export).

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[9] *Gas peaking plant* (also known as peaker plants) are used for grid-balancing services, when electricity demand exceeds supply. They are used as a back-up power source, particularly within networks with higher shares of renewable power generation.

2025

In 2025, hydrogen use in Scotland is relatively moderate, with most demand occurring within the heat and industrial feedstock sectors, followed by the transport sector. Hydrogen meets around 1% of Scotland's annual energy demand.

2032

By 2032, hydrogen is used across all energy demand sectors, particularly to decarbonise heat. Hydrogen use within the transport sector is moderate due to the large uptake of EVs. However, the overall hydrogen demand has grown almost 12-fold since 2025.

2045

By 2045, Scotland meets the net-zero target, with hydrogen being at the core of this energy transition. All energy sectors use hydrogen to some extent, with the heat sector being the most prominent. The use of hydrogen within the transport sector is about 50% lower compared to the full potential scenario. Most of this hydrogen is used for larger service vehicles and fleets within the public sector. Some trains, ferries and small domestic aircrafts connecting remote airports also use hydrogen. Hydrogen blending within the gas network is the main driver of Scotland's hydrogen use in 2045.

Business as Usual Scenario

In this scenario, hydrogen demand in 2025, 2032 and 2045 plays only a supporting role within the decarbonisation efforts in specific sectors and more remote regions. This scenario was created by using the inputs from Scenario C within the SHA, which assumed wider electrification to meet the 2045 net-zero target compared to the other two scenarios.

2025

In 2025, hydrogen is used only within the transport and industrial feedstock sectors, and even there only to a limited extent, 0.228 TWh and 0.175 TWh, respectively. Most of this hydrogen is used on Scotland's islands in the food and drink industry, and within some public transport hubs, such as Aberdeen. Hydrogen is not used in the heat and electricity sectors. The overall hydrogen use is negligible compared to the overall energy demand in Scotland, less than 0.5%.

2032

In 2032, hydrogen demand has grown nearly 20-fold since 2025, across all demand sectors. Hydrogen is now used within the transport sector (almost 2 TWh), heat (almost 3 TWh), industrial feedstock (almost 2.5 TWh) and as a back-up electricity generation – gas-fired peaking plants (0.7 TWh).

Hydrogen is now being blended in the local gas grids, particularly in the north east and more rural areas of Scotland. Hydrogen meets around 5% of the total energy demand in Scotland.

2045

In 2045, Scotland meets the net-zero target with hydrogen playing a supportive role within the energy transition. Hydrogen use had increased approximately 3-fold between 2032 and 2045, accounting for more than 20 TWh annually. The most significant uptake of hydrogen technologies has been seen within the larger vehicles, low-grade heating and industry. Most hydrogen systems are co-located (i.e. hydrogen is generated local to point of use) but there is also some hydrogen blending and tube trailer distribution to supply the hydrogen refuelling station across Scotland.

2.2.4 Regional Demand Projections Comparison

The use of hydrogen strongly depends on the scenario assumption, which results in various future demand projections. However, all these scenarios show that hydrogen use across Scotland will be relatively low in the short term (2020-25). It is likely to grow more than 10-fold in the medium term (2025-32), and then increase around 3 times between 2032 and 2045 to meet Scotland's net-zero target.

Figure 2.11 shows hydrogen demand projections for Scotland, UK and EU. Due to Scotland's abundant offshore wind resource, it can be anticipated that Scotland's green hydrogen production will have the potential to exceed Scotland's hydrogen demand in the future. Therefore, the UK and EU hydrogen demand projections showed are used in Section 3.2 to estimate how much hydrogen could be used for domestic supply (to rest of the UK), or international export (to continental Europe), once Scotland's hydrogen demand is met.

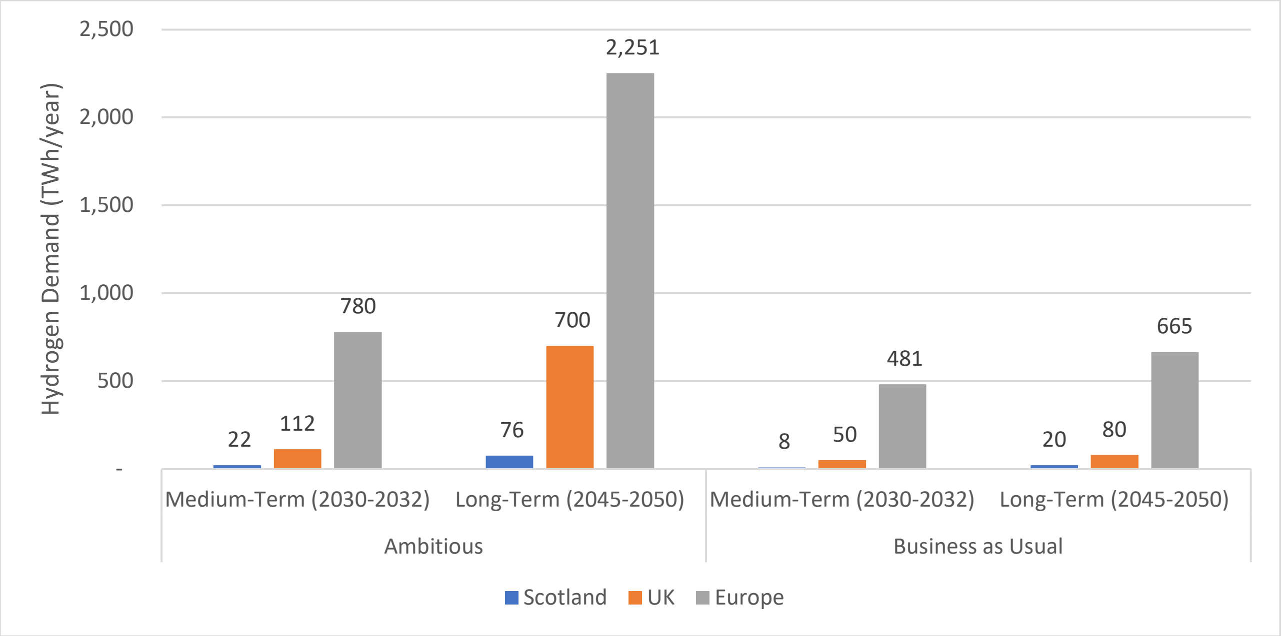

Figure 2.11. Hydrogen Demand Projections in medium to long term

The EU hydrogen demand projections are based on Figure 2.6. The UK projections are based on Xodus' internal modelling projections, which are aligned with The UK Clean Growth Strategy where possible (UK Gov, 2017). Scotland's hydrogen demand projections were taken from Section 2.2.3.

2.2.5 Summary

- Currently worldwide demand for hydrogen is used as chemical feedstock and synthesised from fossil fuelled starting materials. This will change and branch into other sectors and there is a need for clean fuel.
- Trends in Europe show that the demand for hydrogen is increasing. Over the next 12 years, the sector that will grow the largest will be heating, In the next 30 years, the biggest market will be transportation by 2050.

This trend is different to those seen in Scotland which shows the largest sectors as heating > industrial feedstock > transportation by 2045. This is due to the geographical location of Scotland, where a larger portion of energy is used for heating. The rest of the UK requires equal amounts of energy for heating and transportation.

2.3 Hydrogen Demand Hubs Mapping

The following section provides an overview of the location of existing and future hydrogen projects in Scotland, the rest of the UK and continental Europe. The collation of existing hubs focused on grey hydrogen production in particular from SMR, partial oxidation (POX)[10], and as a by-product from other chemical productions.

In the absence of hydrogen demand data at present, it was deemed reasonable to assume that future hydrogen hubs are likely to be located to where existing hydrogen production hubs currently exist in the UK and the rest of Europe. Understanding the location of existing hydrogen hubs indicates where green hydrogen could begin to replace grey hydrogen in the short to medium term, since the demand for hydrogen is already there. These demand centres could potentially be target locations for Scotland to replace existing grey hydrogen and export green hydrogen to. It should be highlighted that these existing hydrogen hubs (chemical industry) are only one of many industries where green hydrogen can play a key role in the future decarbonisation efforts.

This section also provides a location overview of existing low-carbon hydrogen projects in operation and a lookahead into future approved hydrogen projects (currently in their initial concept, pre-construction or construction stages) based in Scotland, rest of the UK and continental Europe, which are. This will provide a reasonable comparison against existing grey hydrogen projects in these regions in order to determine whether any future hydrogen hub locations and therefore demand centres, are closely located to existing grey hydrogen hubs. This is a fast-evolving sector and while this report has attempted to capture the current snapshot as comprehensively as possible, it is recognised that there may be additional projects, especially if only recently announced.

The European maps also show the existing offshore pipeline infrastructure surrounding Scotland. It should be noted that the pipeline layer is presented only to provide an overview of the existing pipeline connections between Scotland and the rest of Europe without considering which pipelines could be suitable to be repurposed for hydrogen use. Further analysis of Scotland’s existing pipeline infrastructure is discussed in Section 3.3.

2.3.1 Existing Hydrogen Demand Hubs

The existing grey hydrogen production hubs in Scotland, the rest of the UK and continental Europe have been mapped out and are shown in Figure 2.12. The hubs sizes are based upon their hydrogen production capacity size. It should be noted that the mapping has considered both compressed gas and liquified hydrogen. It should also be highlighted that liquefied hydrogen plants account for less than 1% of the overall capacity.

It can be seen that there are only two grey hydrogen production plants in Scotland - the Air Products SMR plants in Greenock, and the Petroineos’ plant in Grangemouth. Due to lack of data availability with respect to the actual hydrogen production capacity in Grangemouth, it was assumed that the SMR plant is able to produce the same amount of hydrogen as that operated by BOC in Teesside, Middlesbrough, at circa 88,500 kg/day based on a hydrogen study previously performed by Xodus for the OGTC (Xodus, 2019).

The majority of SMR facilities in the UK are based in England and represent a potential source of demand if the existing UK grey hydrogen sector was to become decarbonised by Scotland’s green hydrogen. Blue hydrogen is a potential competitor in this sector, dependent on the further deployment of CCUS.

Regarding continental Europe, existing hydrogen production plants are predominantly located in Germany, Netherlands, Belgium, France, Spain and Italy. Although not all these countries are located within close proximity to Scotland, hubs located in Northern Europe could become hydrogen importers of green hydrogen produced in Scotland. Especially Germany and the Netherlands could become major importers, as these countries currently produce more than 50% of the total hydrogen production in Europe.

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[10] Partial oxidation is a chemical reaction method in which natural gas or heavy hydrocarbons are partially combusted in a reformer, producing a hydrogen-rich syngas

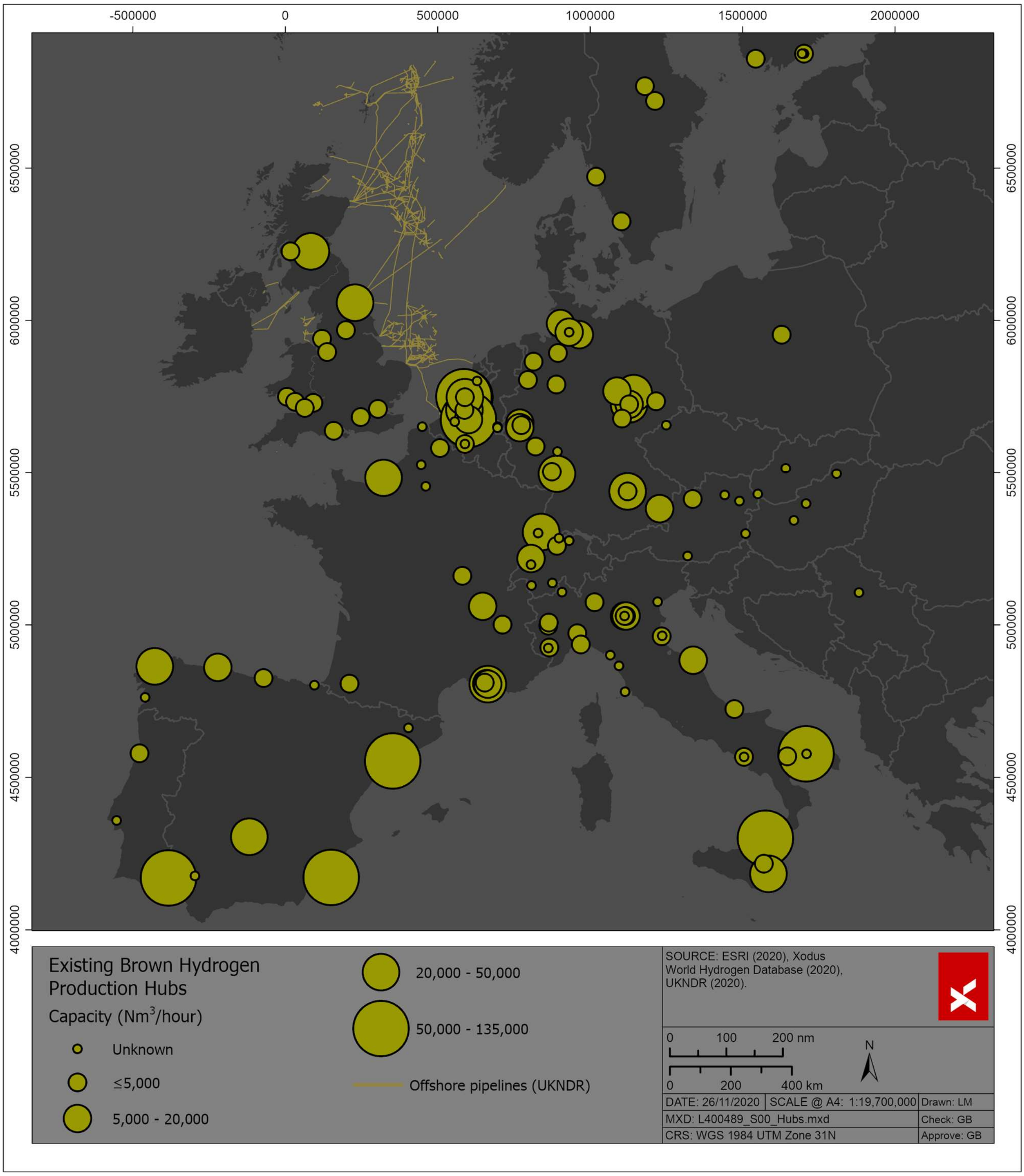

Figure 2.12: Existing Grey Hydrogen Production Hubs in Europe

2.3.2 Low-Carbon Hydrogen Demand Hubs in Scotland

Existing and proposed low-carbon hydrogen projects in Scotland are shown in Figure 2.13. It should be highlighted that these include not only operational projects but also planned projects, currently in their initial concept, pre-construction or construction stages. These projects have been coloured based on the type of projects. It should be highlighted that analysis was based on the number of projects planned in each region in the absence of plant capacity information. The project locations can then be compared with the existing hydrogen hubs to assess whether the existing demand centres trend are still valid for future projects.

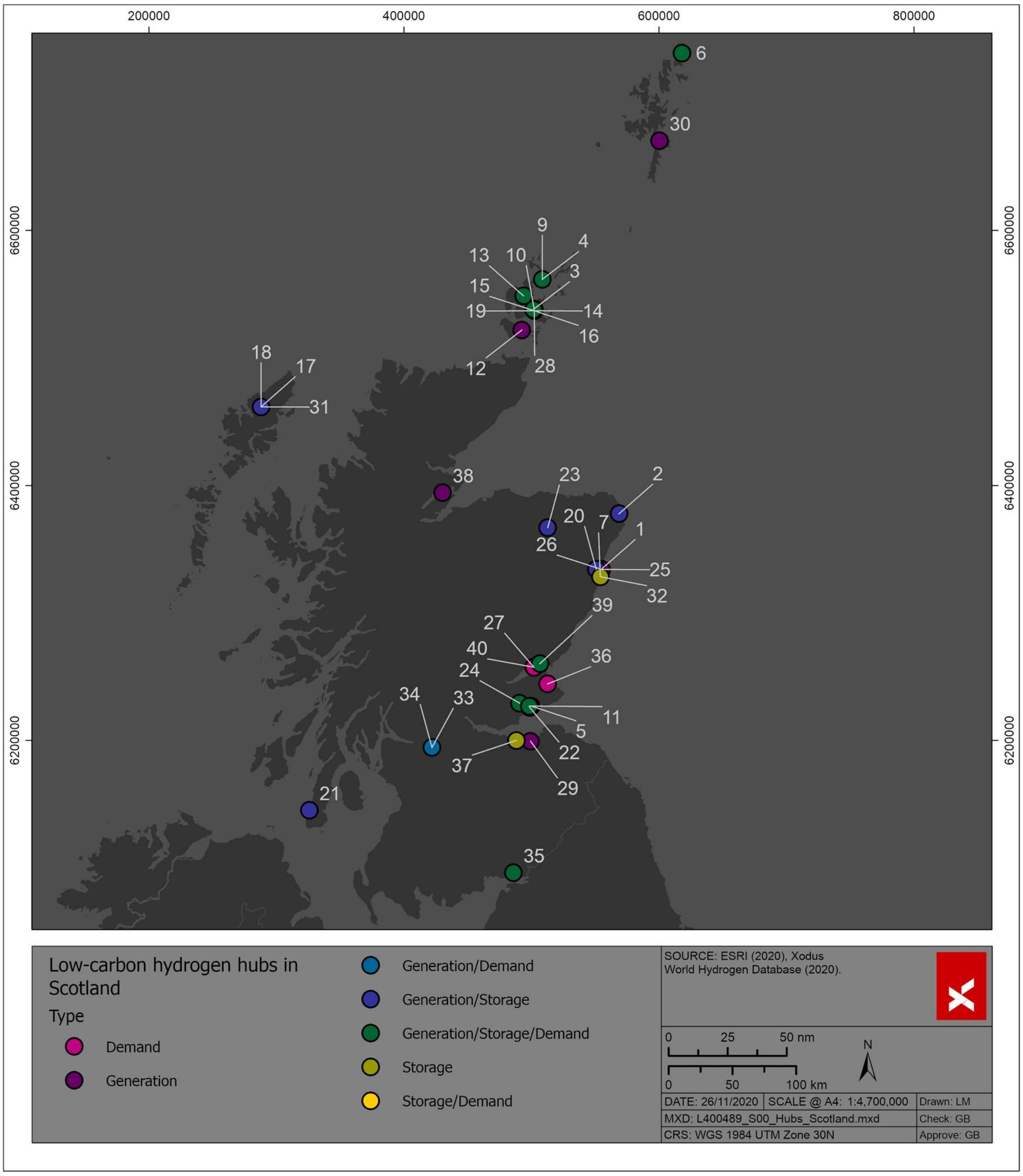

Figure 2.13: Future Hydrogen Hub Projects in the UK

It can be seen that Scotland has been very active in developing pilot hydrogen projects across the country. The map shows a total of 40 hydrogen projects in Scotland either operating or in the project pipeline. This demonstrates Scotland’s dedication to build upon its hydrogen ground-breaking projects such as Surf’n’Turf in Orkney, OHLEH in the Western Isles or hydrogen buses in Aberdeen. Figure 2.13 also shows that the majority of projects include green hydrogen production (dark purple, dark blue, light blue and dark green colours), which supports the idea of Scotland being a green hydrogen production hub (due to its abundant renewables resources) and potentially export the surplus hydrogen to the rest of the UK and continental Europe in the future. Hydrogen project titles shown in the map are summarised in Table 3.1

Table 2.1 Scotland's low-carbon hydrogen projects

Reference	Hydrogen Project Titles	Reference	Hydrogen Project Titles
1	High V.LO-City	21	HyGEN
2	Acorn CCS and Hydrogen	22	HyGEN
3	BIG HIT	23	Huntly Hydrogen
4	Surf n' Turf Orkney	24	Hydrogen 100
5	Levenmouth Hydrogen Office	25	HyTrec2
6	PURE	26	Aberdeen Vision
7	H2 Aberdeen Hydrogen Bus	27	JIVE and JIVE 2
8	Dolphyn	28	HySEAS3
9	ReFLEX	29	SeaFuel
10	HySpirits	30	ORION Project
11	Project Methilltoune	31	HyFlyer
12	HOP Project	32	Aberdeen Hydrogen Hub
13	Orkney Green Ammonia Plant	33	Green Hydrogen for Glasgow
14	ITEG	34	Hydrogen Dual Fuel Gritters
15	PITCHES	35	CX Project
16	Orkney H2 Strategy	36	Hydrogen Accelerator
17	Outer Hebrides Local Energy Hub (OHLEH)	37	HyStorPor
18	Scottish Western Isles Ferry Transport using Hydrogen (SWIFTH2)	38	Cromarty Firth Green Hydrogen Hub
19	HyDIME	39	Michelin Scotland Innovation Parc
20	HyGEN	40	Dundee Hydrogen Refuelling Station

2.3.3 Low-Carbon Hydrogen Demand Hubs in the Rest of the UK and Continental Europe

Existing and proposed low-carbon hydrogen projects in the rest of the UK and continental Europe are shown in Figure 2.14. Similarly to the Scotland hubs mapping, these include both, existing and planned projects. They have been coloured based on the type of projects, and in the absence of plant capacity information, the basis of the mapping has considered the number of future hydrogen hubs and the type of projects in each country. This provides an indicative forecast into the likely location of future hydrogen demand centres in Europe.

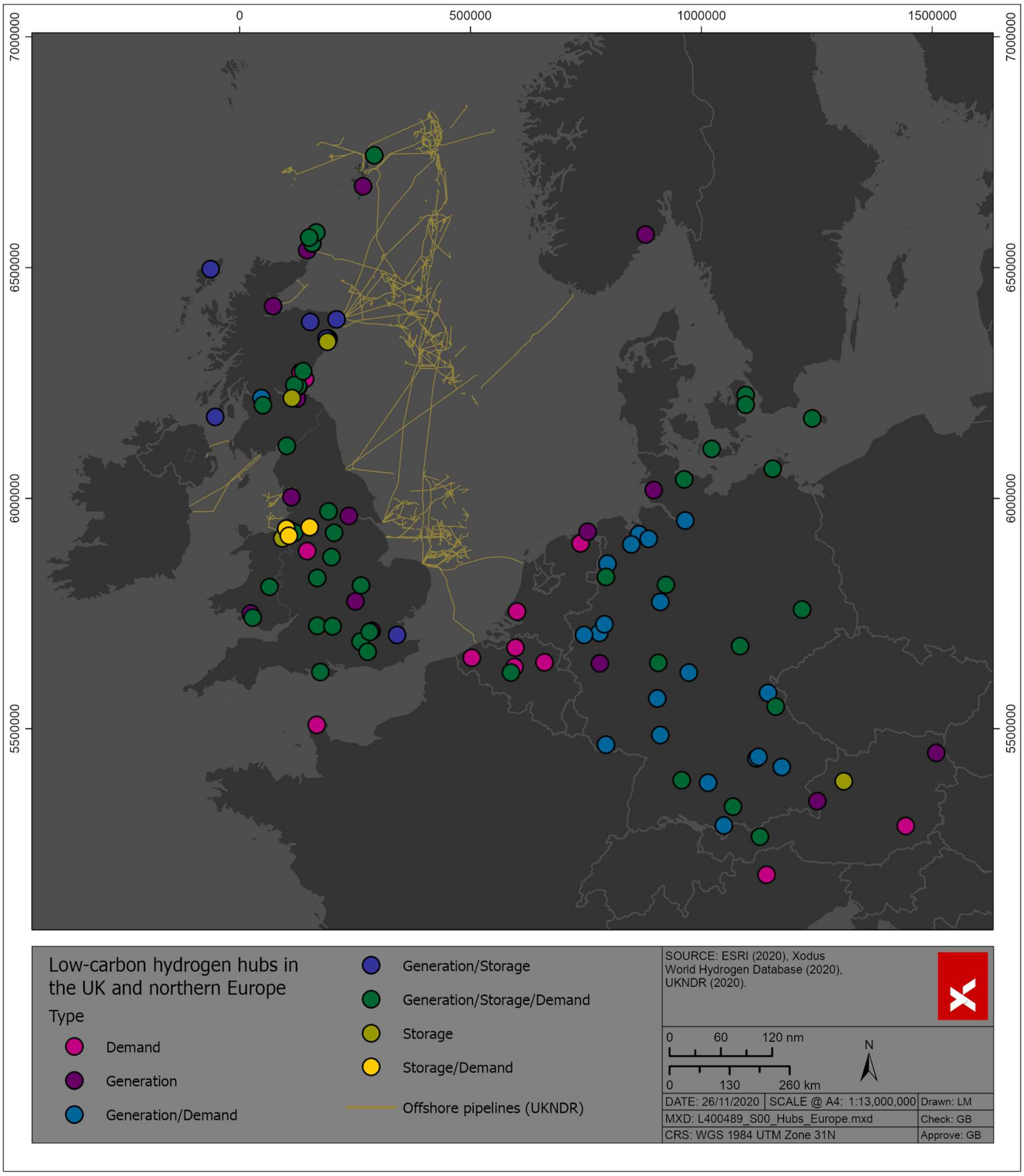

Figure 2.14: Future Hydrogen Hub Projects in Europe

Regarding domestic export opportunity, it can be seen that England could become an importer of Scottish green hydrogen. Although the majority of existing and proposed projects in England currently consider matching hydrogen supply and demand on-site, larger demand projects in the future may require more hydrogen than can be produced locally. Considering Scotland's vast offshore wind resources, green hydrogen could be exported particularly to Northern England to meet future hydrogen demand.

Regarding international export opportunity, it can be seen the vast majority of planned hydrogen projects are located in Germany, which aligns with the recent announcements made by the German Government. Another potential importer of Scotland's green hydrogen could be Belgium, which has several hydrogen demand projects in the pipeline.

Whilst Netherlands may not yet be demonstrating as many hydrogen projects, it is effectively one of the hubs for the movement/import of energy (mostly fossil fuels) into Europe. Therefore, it may reasonably be expected that they will follow, and there exist hydrogen cooperation plans such as The Hydrogen Valley (Hyer, 2019).

The map also shows that there are existing pipeline connections to Belgium and the Netherlands. As discussed in more detail in Chapter3, opportunity may exist to repurpose these pipelines for hydrogen export to Europe. Further detailed analysis is required to assess pipeline opportunities.

Germany, the Netherlands and Belgium are likely to become the leaders in the number of hydrogen demand projects, which suggest their suitability as potential target locations for Scotland to export green hydrogen to in the future. The high number of future hydrogen projects in these three countries can be partially attributed to the fact that that most of the cities where these projects would be located, are densely populated, leading to a higher demand and that Germany, the Netherlands and Belgium have very strong and ambitious climate change policies attempting adherence to the Paris agreement.

It should be noted that whilst Spain, which is currently a large producer of hydrogen in Europe, does not look to have secured and confirmed as many future hydrogen hub projects as other European countries, the country still has potential in leading hydrogen production for Europe due to its substantial solar and wind resources. Consequently, for Scotland, Spain could become one of the main green hydrogen export competitors if they decided to harness their abundant renewable energy resources for green hydrogen production.

2.3.4 Other Regions with Green Hydrogen Export Potential

Based on the recent announcements, Portugal could become Scotland's main competitor with regards to green hydrogen export to Northern Europe. In September 2020, The Portuguese and Dutch Governments agreed on a project to export green hydrogen from Sines to the Port of Rotterdam, Europe's largest seaport (PV-Magazine, 2020). The project will aim to develop a strategic export-import value chain to produce and transport green hydrogen within continental Europe. It can be expected that there will be more green hydrogen projects announced in Portugal, following the launch of Portuguese national hydrogen strategy in May 2020, as well as the Portuguese Government's recent call for hydrogen projects, which attracted more than £14bn of proposed investments (PV-Magazine, 2020).

Scotland's green hydrogen export sector may not only need to compete with other European countries with abundant wind and solar resources, such as Portugal, but also with countries located in Northern Africa and Middle East. Considering that around 80% of green hydrogen production costs are associated with the cost of electricity input (Committee on Climate Change, 2018), countries with very low cost solar will be able to produce green hydrogen cheaper that Scotland's offshore wind. In July 2020, the Al Dhafra facility in the United Arab Emirates secured world's cheapest solar deal with a 2GW capacity and at £10.4/MWh of a levelized cost of electricity (Recharge, 2020). Even with the most ambitious cost reduction curve for Scotland's offshore wind, this electricity cost is not realistically achievable. However, green hydrogen also incurs cost for water sourcing, purification and desalination. Regions such as the Middle East with high solar energy potential may likely generally be areas of higher water scarcity and higher cost of water supply and treatment. It has been beyond the scope of this study to evaluate LCOH for representative solar green hydrogen production, but it would be wrong to conclude a compelling cost advantage based purely on lower cost of electricity alone.

Additionally, exporting green hydrogen internationally involves not only costs associated with production but also with storage and transportation of hydrogen. The current state of hydrogen transportation over long distances is still at its infancy, particularly when it comes to shipping. There are some pilot projects looking into shipping hydrogen via liquefication, ammonia or liquid organic carriers, which are further discussed in Section 3.3. Notably in June 2020, Germany signed green hydrogen cooperation agreement with Morocco to import green hydrogen by using Morocco's abundant solar resources (Fuel Cells Work, 2020). These are the first signs of Scotland's potential competition against countries beyond Europe.

Although the future costs associated with these hydrogen shipping technologies are uncertain, preliminary estimates suggest a cost range of at least £1-£2.3/kg depending on the transportation method used. In the future, exporting hydrogen as ammonia is projected to cost at least £1/kg, liquefied hydrogen £2.2/kg and liquid organic hydrogen carriers £2.3/kg (Macquarie, 2020) (BloombergNEF, 2020). It should be highlighted that all these projections consider optimistic assumptions within each technology.

These hydrogen shipping projections could then be added on top of the hydrogen production estimates and compared to the cost of Scotland's green hydrogen export analysed in Section 4.2 Due to the opportunity of using hydrogen pipelines to export Scotland's green hydrogen to Northern Europe, it is likely that Scotland's green hydrogen can remain cost competitive with green hydrogen from Northern Africa or Middle East especially if the cost of hydrogen shipping remains relatively high. Political and regulatory stability may also favour Scottish hydrogen over some potential alternative sources.

2.3.5 Summary

Regionally, it can be concluded that Scotland is on its way to host the highest number of future planned hydrogen projects, followed by England, and Wales. However, it should be highlighted that the scale of these projects has not been compared in the analysis. It is likely that the size of some hydrogen demand projects in England, will be significantly larger than many projects in Scotland, which would make England a larger hydrogen demand hub. Considering Scotland's untapped offshore wind resources and the energy net exporter legacy, it can be anticipated that some of England's future hydrogen demand hubs could be supplied by Scotland's green hydrogen as discussed in Section 3.2.

From the analysis and comparison between existing and future hydrogen hub projects in Continental Europe, there exists a number of major hydrogen users, particularly Germany, the Netherlands and Belgium. These European countries present a significant opportunity within the European market for Scotland to export green hydrogen to in the future.

Although Scotland and Portugal may currently not seem to have direct competitors for green hydrogen export based on confirmed projects, Spain and countries in Northern Africa and Middle East could become notable competitors in the future if they decided to harness their wind and *particularly* solar resources for green hydrogen production and export to Northern Europe.

Considering Scotland's green hydrogen export cost-competitiveness against other regions (particularly out with Europe), it can be expected that Scotland's green hydrogen can remain cost-competitive with Northern Africa's or Middle East's solar especially if the cost of hydrogen shipping remains relatively high. However, further analysis will be required to assess this risk and thoroughly compare regions with abundant solar resources with Scotland's green hydrogen from offshore wind.

2.4 Hydrogen Cost Parity Projections

Green hydrogen has the potential to decarbonise various energy-intensive sectors which currently rely on the use of fossil fuels. This section focuses on calculating the cost of current fuels used in different energy sectors in 2020. These 2020 costs are then used to estimate how these costs are likely to change by 2032.

Cost estimates indicate the end user price of hydrogen equivalent to the cost of use of fossil fuels. Therefore, the values described in this section are the cost parity levels at which hydrogen would need to be sold for in order to be competitive with its fossil fuel equivalent for the same service. Put another way, the higher the cost parity projections, the better for hydrogen technology. E.g. if cost parity in the transport sector in 2032 is £3.5/kg and the levelised cost of green hydrogen production and delivery to the refuelling station is £3/kg, hydrogen would be cost competitive since it would be able to supply hydrogen at a lower cost than it could sell it for. This section only focuses on the end-user price, whereas hydrogen production costs are assessed later in the report.

Hydrogen can replace various fossil fuel sources across different sectors, which means that the end-user market price will vary significantly across the demand sectors. These markets were assessed independently to establish the corresponding market prices based on the fossil fuel type and sector to meet these demands.

These projections are used later in this study to outline potential subsidies that will be required to decarbonise Scotland’s energy-intensive demand sectors based on the difference between hydrogen supply costs and the cost parity projections.

The assessment included 8 demand sectors, which represent the most likely demand sectors for green hydrogen in the future. The following sectors were included in the assessment:

- Cars
- Buses
- Trains
- Chemical feedstock (ammonia production and refining)
- Ferries
- Aviation
- Heat
- Electricity.

It should be noted that this study only focused on the sale price of the fuels and does not take account of lifecycle or maintenance costs of the technology unless otherwise stated. This is to compare only the operating costs in a given sector. Where applicable, hydrogen cost parity projections are compared to other zero-carbon technologies that are likely to compete with hydrogen technology (such as electric vehicles).

The cost parity outputs are based on the final price paid by consumers. The proportion of fuel duty and value-added tax (VAT) within each sector is assessed in Section 2.4.2.

2.4.1 Modelling Assumptions and Outputs

The cost parity projections for 2032 identified hydrogen cost per sector that the end-users are likely to be willing to pay to replace the use of fossil fuels. The analysis was based on cost parity with the current status quo based on operational costs to deliver the same service. The existing costs of fossil fuels were based on the costs paid by the end-user at the point of delivery (e.g. hydrogen would replace petrol or diesel at the refuelling station). Therefore, factors such as fuel duty and VAT were included in the calculations.

For transport sectors, the table below shows how the hydrogen cost parity was calculated for each sector.

A	Fuel consumption of fossil fuelled sector over distance (litres/100km for example with cars)
B	Hydrogen fuel consumption of equivalent sector (kg/100km for example with cars)
C	Cost of Fossil Fuel (£/litre for example with petrol)
	2020 hydrogen cost parity = [A]/[B]]*[C]
	2032 hydrogen cost parity (£/kg)

The average quantity unit (distance/volume/power) for both the fossil fuelled technology [A] and its hydrogen equivalent [B] is determined. The cost per quantity unit [C] of the appropriate fossil fuel is then used to determine what the cost of hydrogen would need to be, the cost parity, in 2020 to equal the cost of its fossil fuelled equivalent.

For sectors that do not have a hydrogen technology equivalent, energy content values of the fossil fuel and equivalent amount of hydrogen are compared to determine the hydrogen cost parity.

The hydrogen cost parity for 2032 was then determined using fuel cost projections. For petrol, diesel and marine gas oil (MGO), projections taken from 2019-2032 in the US (EIA, 2020) were used to obtain a factor of change and applied to UK government values in 2019.

For natural gas projections and kerosene for aviation, UK projections from 2015-2035 were taken from Statista and values for 2032 were extrapolated (Statista, 2020) (Statista, 2020). Since steam methane reformed hydrogen uses a natural gas feedstock, projections for chemical feedstock hydrogen were also projected via this method.

2.4.1.1 Cars (light-duty road transport)

Key assumptions and results

A	Average UK petrol car fuel consumption	5.46	litres/100km
B	Average hydrogen fuel consumption of Toyota Mirai	0.94	kg/100km
C	Cost of UK petrol in 2019	1.25	£/litre
	2020 hydrogen cost parity [A]/[B]*[C]	7.3	£/kg
	2032 hydrogen cost parity (£/kg)	**7.8**	**£/kg**

The bestselling fuel cell electric vehicle (FCEV) in the world is Toyota Mirai, with a fuel economy of 0.94 kg of hydrogen / 100 km based on the Worldwide Harmonised Light Vehicle Test (WLTP) combined cycle (Grange, 2020). An average petrol car in the UK uses 5.46 litres of petrol per 100 km (GOV UK, 2019). This value also aligns with the WLTP combined cycle of smaller petrol cars similar sized to Toyota Mirai (Grange, 2020). Considering the average cost of unleaded 95 Octane in the UK in 2019-2020 (UK Gov, 2020), average light-duty vehicles pay on average £7.3 per 100 km. This cost is likely to increase to £7.8 by 2032, based on petrol cost projections for 2032 (EIA, 2020).

Considering the increasing market penetration of hybrid electric vehicles and the fact that an average UK petrol car fuel consumption varies significantly, Toyota Mirai was also compared to a new hybrid electric vehicle, which is more efficient than an average UK petrol car.

Key assumptions and results

A	New hybrid electric car fuel consumption	4.32	litres/100km
B	Average hydrogen fuel consumption of Toyota Mirai	0.94	kg/100km
C	Cost of UK petrol in 2019	1.25	£/litre
	2020 hydrogen cost parity [A]/[B]*[C]	5.7	£/kg
	2032 hydrogen cost parity (£/kg)	**6.2**	**£/kg**

In this scenario, Toyota Mirai was compared to Toyota Prius electric hybrid based on its WLTP combined cycle (Toyota, 2018). The remaining assumptions remained identical to the previous calculations, which resulted in lower cost parity outputs compared to the average UK petrol vehicle. It should be highlighted that plug-in electric hybrid cars were not included in the analysis.

Competition with other zero-carbon technologies

Although this study is predominantly focused on the cost competitiveness of hydrogen technology versus fossil fuels, it should be highlighted the main competitor of FCEVs in 2032 will be battery electric vehicles (BEVs). Both technologies can be powered *via* zero carbon fuels (green hydrogen or renewable electricity), therefore contributing towards Scotland's decarbonisation efforts within the transport sector. Although pure energy input costs are likely to favour BEVs, particularly in areas with sufficient electricity grid capacity to accommodate charging, FCEVs may become a feasible option for light-duty vehicles that require frequent refuelling and operate in areas with already constrained electricity grids.

It will cost approximately £2.8 to travel 100 km in a BEV in 2032, assuming home charging of Nissan Leaf and future electricity retail cost projections (Nissan, 2020) (Statista, 2020) (UK Gov, 2019) . Therefore, hydrogen used in a Toyota Mirai would need to cost £2.8/kg to become cost competitive with BEV electricity charging at home. On the other hand, charging a BEV via a 50-150kW rapid charger is significantly faster and more expensive compared to home charging. Assuming current rapid charging costs and future electricity cost projections, this would equate to a cost parity projection of £7.9/kg for hydrogen dispersed at a refuelling station in 2032 (Shell, 2020) (Statista, 2020). This value is close to the projected cost parity with average petrol cars.

A range of hydrogen fuel cell range extenders have also been developed and are in operation in Orkney. This uses hydrogen fuel cell technology to power the batteries in BEVs and provides additional mileage without recharging the battery at a fixed power supply (SeaFuel, 2019). This combines both technologies and could be another avenue where FCEV technology is taken up.

Although this report is predominantly focused on the upstream and midstream aspects of hydrogen technology, it can be expected that *some* light-duty vehicles sold in 2032 will be FCEVs, rather than entirely BEVs.

2.4.1.2 Buses

Key assumptions and results

A	Average diesel hybrid bus fuel consumption	32.3	litres/100km
B	Hydrogen bus fuel consumption	8.57	kg/100km
C	Cost of UK diesel in 2019	1.32	£/litre
	2020 hydrogen cost parity	5.0	£/kg
	2032 hydrogen cost parity (£/kg)	**5.5**	**£/kg**

An average diesel hybrid bus operating in London has a fuel economy of 7.3 to 8.8 miles per gallon (mpg) (Lin, Partridge, & Bucknall, 2016). A fuel consumption of 8.8 miles per gallon was selected for the calculations, assuming that these are new buses that would be competing with new hydrogen buses. The Aberdeen hydrogen refuelling station, Kittybrewster, can produce up to 300 kg of hydrogen a day to refuel 10 buses to travel up to 350 km (The Engineer, 2020). This aligns with the fuel economy outlined by Hydrogen Europe, which states that new hydrogen fuel cell buses use 8 to 9 kg per 100 km (Hydrogen Europe, 2017) [11]. Therefore, hydrogen parity for buses to replace diesel is estimated to be 5/kg of hydrogen in 2020. Hydrogen could be sold for £5.5/kg in Scotland in 2032 to achieve the cost parity with an average hybrid bus based on diesel cost projection for 2032 (EIA, 2020).

Competition with other zero-carbon technologies

Similarly to light-duty vehicles, hydrogen powered buses sold in 2032 will have to compete with battery electric buses, as both of them can use zero-carbon fuels. Hydrogen buses are likely to become more competitive with battery electric buses particularly for longer distances and when fast and frequent refuelling is required.

The energy consumption of battery electric buses can range between 1 and 3.5 kWh/km, depending on many parameters, such as bus technology, traffic conditions, number of passengers or route profile (Pamula & Pamula, 2020). Assuming an average energy consumption rate of 1.41 kWh/km as outlined in the report and future electricity cost projections (slow charging), the cost parity of hydrogen buses versus battery electric in 2032 would be £3/kg. However, slow charging may only be available for shorter, less frequent routes.

This cost parity trend is similar to light-duty vehicles; buses with relatively low daily mileage will be able to be charged overnight, profiting from lower electricity costs and lower charger capacity requirements. Buses that will need to be recharged frequently and quickly throughout the day be more suitable for hydrogen technology.

2.4.1.3 Trains

Key assumptions and results

A	Average diesel train fuel consumption	49.28	litres/km
B	Hydrogen fuel cell train consumption	1.0	kg/km
C	Cost of UK diesel in 2019	0.85	£/km
	2020 hydrogen cost parity	3.1	£/kg
	2032 hydrogen cost parity (£/kg)	**3.4**	**£/kg**

Average per-passenger fuel economy of diesel trains varies significantly depending on the type of journey. E.g. intercity trains are more efficient compared to commuter trains (58.93 miles per passenger US gallon compared to 39.63) (AFDC, 2020), since they experience fewer stop-start situations. An average fuel economy between intercity and commuter trains was used for the calculations and multiplied by 300 passengers to align with the hydrogen fuel cell train capacity - Alstom iLintFCH. The train consumes 0.275 kg of hydrogen every kilometre and has a passenger capacity of 300 (Hydrogen Europe, 2018). It should also be noted that diesel used for trains attracts lower Fuel Duty compared to road transport (such as cars or buses), as can be seen in Table 2.2

Competition with other zero-carbon technologies

Regarding the competition of electric versus hydrogen trains, it is likely that electrified train lines will be used in densely populated areas with frequent routes, whereas hydrogen powered trains and battery electric trains may split the market with battery powered trains serving shorter routes and hydrogen powered trains serving

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[11] It should be highlighted that the average fuel economy of hydrogen buses is uncertain. One report stated a fuel economy of 10.3 kg of hydrogen per 100 km (Element Energy, 2017), which would decrease the cost parity in 2032 from £5.5 to £4.7/kg.

longer routes in remote, rural areas where trains run more sporadically. This is because the electricity infrastructure required to power electric trains is costly and can be justified only when transporting high number of passengers or goods, usually over shorter distances.

2.4.1.4 Chemical Feedstock

Key assumptions and results

2020 hydrogen cost parity	2.0	£/kg
2032 hydrogen cost parity (£/kg)	**2.6**	**£/kg**

Currently in the UK the cheapest way to purchase large quantities of grey hydrogen, would be for the supplier to build a dedicated SMR on site connected to the NTS and convert the hydrogen from natural gas. The quoted cost for such a supply is approximately £2/kg of hydrogen produced, which covers CAPEX and OPEX for the equipment required and supply of natural gas (TNEI and Pure Energy Centre, 2020).

SMR produces hydrogen from methane with a by-product of carbon dioxide which is vented to atmosphere. This is the most common way to produce hydrogen at present and does not incorporate carbon capture (this would add approximately £0.5/kg of hydrogen produced). Cost parity of green hydrogen is estimated to be £2.6/kg by 2032, based on the future projections of natural gas cost in the UK (Statista, 2020).

It should be highlighted that existing hydrogen producers (SMR operators) are not necessarily the same companies as the hydrogen end-users. These hydrogen merchants currently sell hydrogen in the UK for around £2/kg. Therefore, green hydrogen would have to directly compete with these merchants that own SMR facilities. If green hydrogen can offer equal (or lower) price than these existing producers, then the hydrogen end-user would be likely switch to green hydrogen. However, a lower cost parity projection would apply to hydrogen end-users who already own an existing SMR facility to produce their own hydrogen, as their facility is sunk cost. The green hydrogen supply this has to compete with operating costs only, which are mainly related to the use of natural gas (rather than paying the full hydrogen merchant price).

Competition with other zero-carbon technologies

There is no alternative technology to compete with hydrogen, which is already used as chemical feedstock. The only future competition for green hydrogen would be blue hydrogen. However, this section is focused on the demand side rather than supply. Therefore, the dominant role of hydrogen used as key feedstock to the chemical industry is likely to remain in the future, with the only difference being the type of hydrogen supplied.

2.4.1.5 Ferries

Key assumptions and results

Marine gas oil ferry plant efficiency	0.37	-
Hydrogen fuel cell ferry plant efficiency	0.4	-
LHV of marine gas oil	11.89	kWh/kg
LHV of hydrogen	33.3	kWh/kg
Cost of UK marine fuel in 2019	0.5	£/litre
2020 hydrogen cost parity	1.5	£/kg
2032 hydrogen cost parity (£/kg)	**1.9**	**£/kg**

Based on the Scottish Western Isles Ferry Transport using Hydrogen (SWIFTH2) project (Point and Sandwick Trust, 2019), an average MGO plant efficiency is 0.37 compared to a hydrogen fuel cell plant efficiency of 0.4. These efficiencies combined with Lower Heating Values of each fuel were then used to calculate the cost parity. The average current MGO cost in Scotland is £0.50/litre (TNEI and Pure Energy Centre, 2020) (Point and Sandwick Trust, 2019)[12].

Competition with other zero-carbon technologies

Using green hydrogen to power ferries is likely to become a feasible low-carbon option, rather than using battery electric ferries. Battery electric ferries may be used only for very short journeys. Space restrictions and weight allowance are important aspects of seagoing transport, which is why batteries are not expected to become widely deployed within the ferry sector compared to hydrogen systems.

2.4.1.6 Aviation

Aside from small scale trials currently being conducted under the HyFLYER programme by ZeroAvia, no comparable hydrogen aviation technology exists in the larger scale.

Key assumptions and results

LHV Kerosene	11.94	kWh/kg
LHV Hydrogen	33.3	kWh/kg
Average UK kerosene retail price for aviation in 2020[13]	0.42	£/kg
2020 hydrogen cost parity	1.2	£/kg
2032 hydrogen cost parity (£/kg)	**1.6**	**£/kg**

Using hydrogen to decarbonise the aviation sector is an emerging concept, with exact technology and set-up still unknown. For example, hydrogen could take up more space, potentially taking away seats in what would normally be the passenger cabin or space in the cargo hold. Lower Heating Values of hydrogen and kerosene were compared only for a very high-level cost parity indication. Further information about hydrogen-powered aviation can be found in the recent EU report (FCH JU, 2020).

Average UK aviation kerosene retail price in 2020 was £0.42kg based on aviation kerosene density of 0.81kg/l (Chevron, 2007) and cost of £0.34/l (Statista, 2020). This means that hydrogen would have to cost £1.6/kg in 2032 to compete with kerosene used in aviation based on future price projection for kerosene in the UK (Statista, 2020) and assuming its use does not suffer from any other inconvenience, such as lower payload volumes, which are likely to occur due to hydrogen's lower energy density.

Competition with other zero-carbon technologies

Similarly to seagoing ferries, hydrogen planes are likely to be more suitable for longer (transatlantic) journeys, whereas battery electric planes may only be able to compete with hydrogen technology on journeys that are shorter and carry less cargo. Future zero-carbon planes may also be powered by synthetic fuels. However, synthetic fuels also require green hydrogen as a zero-carbon feedstock, so the role of green hydrogen in aviation is likely to be significant to meet Scotland's net-zero targets by 2045.

2.4.1.7 Heat

Key assumptions and results

HHV Natural gas	14.5	kWh/kg
HHV Hydrogen	39.4	kWh/kg
Average domestic gas price in Scotland in 2019	44.5	£/MWh
2020 hydrogen cost parity	1.8	£/kg
2032 hydrogen cost parity (£/kg)	**2.3**	**£/kg**

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[12] This cost is similar to Europe's bunker fuel cost in Q4 2019, which was £0.44/kg (S&B, 2020).It should be highlighted that banker fuel cost is fluctuating significantly depending on the oil price. For example, banker fuel cost in April 2020 was only £0.17/kg.

The average domestic gas price in Scotland in 2019 was 4.45 pence per kWh using the average of all payment types (UK Gov, 2020). It should be highlighted that this price is what the average consumer paid in Scotland in 2019, which includes the cost of natural gas supply, transmission and distribution to Scotland's homes. Based on Higher Heating Value (HHV) of natural gas and natural gas cost projections in 2032 (Statista, 2020), hydrogen cost parity equals to £2.3/kg in 2032, as hydrogen contains more energy per mass compared to natural gas. This is the price that hydrogen would have to be sold for to Scotland's domestic consumer to compete with natural gas.

Competition with other zero-carbon technologies

Although natural gas used within the UK heat sector offers a very low-cost parity projection for green hydrogen, it is still likely that hydrogen will be one of the only solutions to decarbonise the UK heat sector. There are other options to deliver zero-carbon heat, such as heat pumps, biomethane or biomass boilers. Particularly heat pumps are likely to be the main competitor of green hydrogen technology. However, it can be expected that heat pumps will not be able to decarbonise Scotland's entire heat sector, especially since the natural gas grid infrastructure is already in existence and extensive and could be converted for hydrogen use in the future.

Although the cost comparison of heat pumps and hydrogen boilers depends on many aspects, it is likely that neither of these technologies will be able to compete with the current cost of natural gas. Progressive incentive (or natural gas disincentive) will be required to decarbonise Scotland's heat sector as discussed in Section 4.3. Considering that Scotland's heat demand accounts for more than half of Scotland's overall energy demand, it is likely that heat pumps and hydrogen systems will have to work hand in hand to decarbonise this 'hard-to-abate' sector.

2.4.1.8 Electricity

Key assumptions and results

LHV Natural gas	13.1	kWh/kg
LHV Hydrogen	33.3	kWh/kg
Average UK wholesale gas price 2019 (HHV)	16.4	£/MWh
2020 hydrogen cost parity	0.5	£/kg
2032 hydrogen cost parity (£/kg)	**0.7**	**£/kg**

The cost parity calculations within the electricity sector is the most challenging due to its dynamic nature. Considering that the vast majority of Scotland's electricity generation already comes from renewables, natural gas is used for electricity generation predominantly when electricity demand exceeds supply to balance the grid. This often coincides with times when the wholesale price of natural gas is significantly higher than average, driven by the increased demand requirements.

If this dispatchable electricity generation currently provided by natural gas peaking plants was to be replaced with green hydrogen, it would require substantial amounts of hydrogen being stored. Dispatchable electricity generation in Scotland is often required when there is not enough wind generation available, therefore hydrogen would have to be stored and readily available to address the supply-demand imbalance. As discussed in Section 3.3, Scotland's large hydrogen storage caverns are primarily located offshore, which would add substantial cost to the dispatchable fuel supply but could offer higher than average market price due to the increased electricity demand requirements.

Assessing the cost of large-scale hydrogen storage or Scotland's hourly/daily electricity supply-demand profile was beyond the scope of this initial study. Therefore, the cost parity results within the electricity sector are only indicative, based on the average wholesale price of natural gas and Lower Heating Values of natural gas and hydrogen, assuming that hydrogen would be burnt in large hydrogen gas turbines to generate electricity. This high-level comparison resulted in a hydrogen cost parity price of £0.7/kg of hydrogen in 2032 to be able to compete with large-scale natural gas-peaking plants based on cost projections for 2032 (Statista, 2020). However, due to the complexity of the topic and the non-inclusion of storage CAPEX and OPEX in the simplified analysis, cost parity with natural gas for electricity is excluded from parity summary figures later in this section

Competition with other zero-carbon technologies

The electricity generation sector is likely to be one of the most difficult for hydrogen technology to enter. Electricity generation from green hydrogen could only be used as a dispatchable, back-up source when renewable generation cannot meet the longer-term electricity demand. This introduces the complexity of seasonal hydrogen storage and additional CAPEX and OPEX for large-scale offshore storage. Whilst it is possible that cavern storage could be replenished during times of low electrical cost (or during period where wind energy is curtailed) , the overall efficiency of converting renewable electricity to hydrogen and then back to electricity is very low and is most likely to be used only as a last resort option.

2.4.2 Assessment of Taxes

Fossil fuels sold and used in the UK fall under different categories based on guidance provided by Her Majesty's Revenue and Customs (HMRC). Since hydrogen could be used to replace various fossil fuels in different sectors Table 2.2, shows fuel duty and VAT assumptions applied within each sector. It is noted that there are complex exemptions in each sector, so these assumptions may not be precise for every individual application in a given sector.

The impact of Fuel Duty and VAT on the cost parity results is shown in Figure 2.15 to highlight the significant effect of existing taxing regime within each sector. For example, fuel duty and VAT significantly influences the final cost of petrol used in cars or diesel in buses, compared to MGO used in ferries, which is exempted from fuel duty and VAT. It should be noted that fuel duty and VAT were based on 2020 rates even for the 2032 cost parity estimates.

Table 2.2 UK fuel duty and VAT in corresponding sectors

Sector	Fossil Fuel Replaced	Taxes		Reference
		Fuel Duty (£/litre)	VAT	
Cars	Petrol	0.5795	20%	(HMRC, 2014)
Buses	Diesel	0.5795	20%	(HMRC, 2014)
Trains	Diesel	0.1114	20%	(fta, 2018)
Chemical Feedstock[14]	Grey hydrogen	0	0	
Ferries	Marine Gas Oil	0	0%	(HMRC, 2019)
Aviation	Kerosene	0	20%	(HMRC, 2014)
Heat	Natural gas	0	5%	(HMRC, 2016)
Electricity	Natural gas	0	5%	(HMRC, 2016)

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[14] It was assumed that brown hydrogen used as chemical feedstock does not attract any tax, since many brown hydrogen users generate their hydrogen on-site and use it as chemical feedstock in the same location.

2.4.3 Summary

The cost parity modelling was focused on current costs and those projected for 2032. The final results are shown in Table 2.3. The table shows Scotland's hydrogen cost parity for each sector in 2032 and the prices that consumers would be likely to pay for the fossil fuel equivalent per sector. The table also highlights what type of fossil fuel would be replaced by green hydrogen, and examples of alternative zero-carbon technologies that are likely to become competitors with green hydrogen in 2032. It should be noted that these are only examples and other alternative technologies can be found in reports that are focused on the demand side.

It should be also caveated that the cost parity calculations in this section is focussed on the supply costs and do not account for costs associated with the end use application, including delivery of green hydrogen from the onshore landfall to point of use. The costs also do not consider any capital costs associated with the adoption of hydrogen (e.g. capital cost of new hydrogen cars). To enable a wide uptake of hydrogen end-use technologies across Scotland, the capital cost for the initial investment in hydrogen technology is likely to require incentives. Such example can be seen in the light-duty vehicle sector, where the capital cost required to buy a hydrogen car is significantly higher compared to an equivalent petrol vehicle.

Table 2.3 Hydrogen cost parity results for 2032 compared to fossil fuel equivalents and their anticipated low-carbon competitors per sector

Sector	2032 Hydrogen Cost Parity (£)		Fossil Fuel Replaced	Alternative Technology Competitor Example
	Including fuel duty and VAT	Excluding fuel duty and VAT		
Average Petrol Cars	7.8	2.6	Petrol	Battery electric vehicles
Hybrid Electric Cars	6.2	2.1	Petrol	
Buses	5.5	2.0	Diesel	Battery electric buses
Trains	3.4	2.1	Diesel	Railway electrification
Chemical Feedstock	2.6	2.6	Grey hydrogen	None
Heat	2.3	2.2	Marine Gas Oil	Battery electric ferries
Ferries	1.9	1.9	Kerosene	Battery / synthetic fuels
Aviation	1.6	1.3	Natural gas	Heat pumps / biomass / biomethane
Electricity	0.7	0.7	Natural gas	Battery / other grid balancing technologies

Table 2.3 indicates that land-based transport is where cost of fuel in demand sectors may be most competitively challenged by hydrogen in 2032, particularly when Fuel Duty and VAT are included. When taxes are excluded, cost parity across the sectors is more evenly distributed, ranging from 1.9 to 2.6 (apart from aviation and electricity sectors which are only indicative and will require further analysis as highlighted in Section 4.3).

It should be highlighted that this chapter does not include transportation logistics cost of getting the green hydrogen to the customer from the onshore landing point. To demonstrate this on an example; the associated costs of delivering green hydrogen to refuelling stations *via* pressurised containers is likely to be significantly higher than direct injection of hydrogen into the national gas grid network to decarbonise the heat sector. Due to the high logistics cost for getting hydrogen to the refuelling stations, and very low logistics cost of the existing pipeline network, the actually cost-competitiveness gap between various sectors is assessed in Section 4.3 to evaluate which sectors are likely to become the most cost competitive with fossil fuels in 2032, and which may require additional support in terms of subsidies.

The analysis revealed that the most difficult sectors for green hydrogen penetration are the ones with the lowest Fuel Duty and VAT under current tax regime. This particularly applies to natural gas, which not only attracts lower taxes but also offers lower emissions abatement potential compared to other fossil fuels as discussed in Section 4.3. This makes the replacement with green hydrogen not only challenging from a direct cost to consumer point of view but also from the environmental perspective. The final 2032 cost parity results assessed in this section are shown in Figure 2.15.

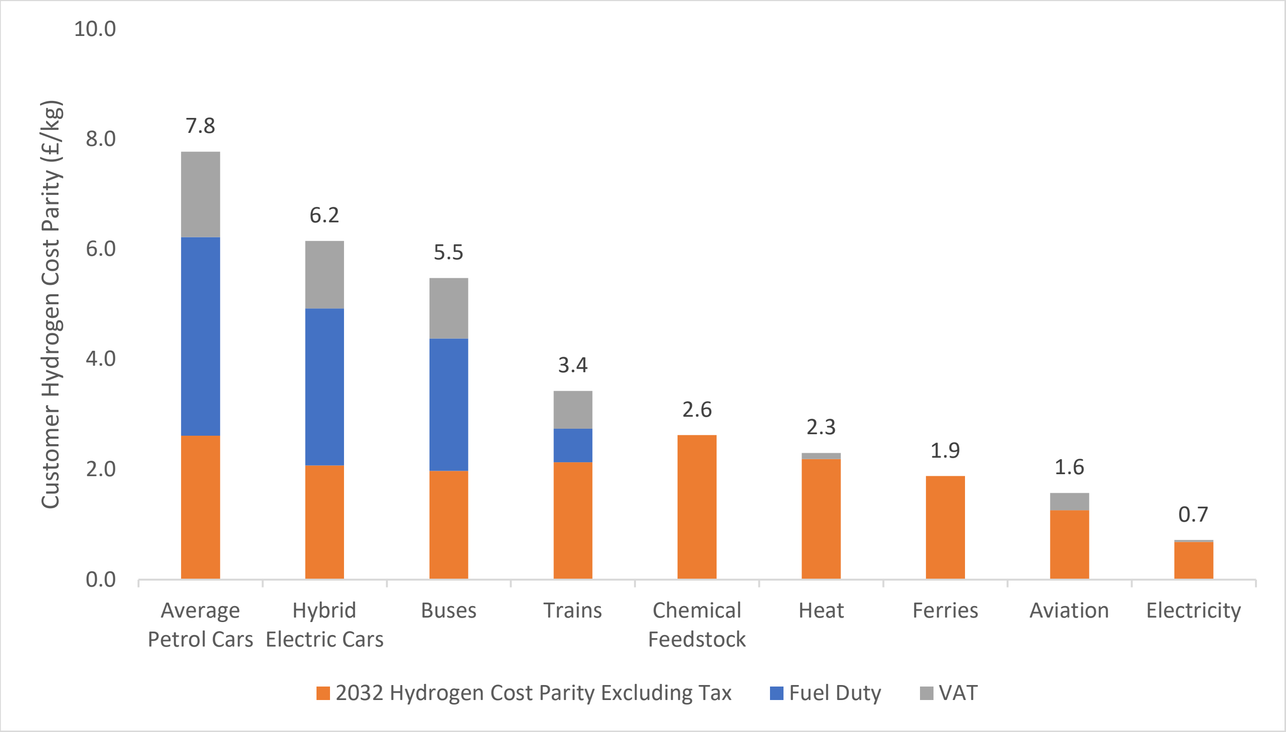

Figure 2.15. Scotland's 2032 hydrogen cost parity summary

3 SCOTLAND’S GREEN HYDROGEN POTENTIAL

3.1 Introduction

Scotland has both a sizeable offshore wind resource, and an extensive offshore and coastal infrastructure and supply chain associated with the long-established oil and gas industry. These are supported by world-class universities and research centres, and innovative energy solution providers.

This section considered the potential of this resource, infrastructure and supply chain to be utilised for green hydrogen production. The following opportunities are examined:

- Analysis of Scotland’s offshore wind resource potential that could be leveraged for green hydrogen production in future.
- The potential suitability of repurposing existing O&G pipelines in the North Sea for transportation of hydrogen, in particular to connect Scotland to Europe to export clean hydrogen to demand hubs in densely populated hubs in Northern Europe.
- The potential suitability of existing terminal and ports for ship-based export of hydrogen
- The current state of the Scottish supply chain to support green hydrogen production.

3.2 Hydrogen Production Modelling

Three development scenarios of offshore wind energy capacity have been developed across the timescales of 2025, 2032 and 2045, to help inform the modelling of the potential amount of hydrogen that could be produced from offshore wind energy in Scotland.

The offshore wind potential was used to create 2045 net-zero scenarios to enable calculation of the amount of green hydrogen (GWh/year) that could be produced from offshore wind to meet Scotland’s hydrogen demand evaluated in Chapter 2, and export surplus hydrogen to the rest of Europe to meet hydrogen demand of the identified hubs outside of Scotland.

This section is focused on creating credible scenarios related to green hydrogen production from offshore wind and highlights Scotland’s potential to become a green hydrogen exporter in the future, which is further assessed in Chapter 4.

3.2.1 Scotland’s Offshore Wind Projections

The offshore wind projections between 2020 and 2045 are based on the following scenarios;

- **Ambitious Scenario**: The most ambitious green hydrogen production scenario in 2025, 2032 and 2045, if multiple leasing rounds in Scotland were undertaken ahead of 2045 and development was promoted beyond the current net-zero targets.
- **Planned Development Scenario**: Optimistic but credible green hydrogen production scenario based on a high capacity of ScotWind leasing and realistic subsequent future offshore wind developments being realised. In addition to the offshore wind development, the roadmap for this scenario assumed political support for green hydrogen production, use and export.
- **Business as Usual Scenario**: Conservative scenario with Scottish offshore wind development continuing at modest pace with limited green hydrogen technology uptake and no additional policy support.

The scenarios have been based on current offshore wind farm policies and targets (apart from the 2045 ambitious scenario which assumes multiple leasing rounds that have not been confirmed to date). They do not represent the total capacity possible if policy was to change or if the entire seabed was to be made available for development.

The capacity values estimated include the current capacity available from fully commissioned offshore wind farm projects estimated at ~900 MW (see Table 3.1). The scenarios produced have not considered the potential for Offshore Wind Farms (OWFs) to secure consent or a CfD or another financial agreement.

Table 3.1 Current OWFs Included in Supply Scenarios

Current Scottish Offshore Wind Farms	**Phase**	**Capacity (max)**	**Current operational OWF capacity**	**Projects included in 2025 scenario**		
				Business as usual	**Planned development**	**Ambitious**
Aberdeen Offshore Wind Farm (EOWDC)	Fully Commissioned	93.2	🟦	🟦	🟦	🟦
Beatrice	Fully Commissioned	588	🟦	🟦	🟦	🟦
Hywind Scotland Pilot Park	Fully Commissioned	30	🟦	🟦	🟦	🟦
Kincardine - Phase 1	Fully Commissioned	2	🟦	🟦	🟦	🟦
Levenmouth demonstration turbine	Fully Commissioned	7	🟦	🟦	🟦	🟦
Robin Rigg	Fully Commissioned	174	**900MW**	🟦	🟦	🟦
Moray East	Under Construction	950		🟦	🟦	🟦
Neart na Gaoithe	Under Construction	448		🟦	🟦	🟦
Kincardine - Phase 2	Pre-Construction	48		🟦	🟦	🟦
Seagreen 1	Pre-Construction	1075		**3400MW**	🟦	🟦
Inch Cape	Consent Authorised	1000			🟦	🟦
Moray West	Consent Authorised	950			**5400MW**	🟦
Dounreay Trì	Consent Authorised	10				🟦
ForthWind Offshore Wind Demonstration Project Phase 1	Consent Authorised	29.9				🟦
Seagreen Extension	Consent Authorised	360				**5800MW**
Berwick Bank & Marr Bank	Concept/Early Planning	3200				
ForthWind Offshore Wind Demonstration Project Phase 2	Concept/Early Planning	53				

The five year look ahead to 2025 considers projects that are currently fully commissioned or established on the development path. The 2032 timescale involves consideration of the ScotWind offshore wind leasing round and a potential maximum capacity of 10 GW. Looking ahead to 2045 and beyond the maximum limits currently established by the Draft Sectoral Marine Plan for Offshore Wind Energy (ScotWind), understanding the potential capacity available to Scotland comes down to understanding the ambitions of the industry and the Scottish Government. The current UK's ambitions (either governmental or industry) range from 50 - 75GW of offshore wind capacity by 2050 in order to achieve net-zero, as highlighted by the Committee for Climate Change Net Zero Technical Report (Committee on Climate Change, 2017). The Scottish Government has set the target of achieving net-zero by 2045 acknowledging the need for more offshore wind energy as outlined in the Draft Offshore Wind Policy Statement and Scottish Renewables have clearly outlined the ambition for Scotland to contribute 40-45% of the total 75 GW target (Scottish Renewables , 2020). The 2045 ambitious scenario looks even beyond this target and outlines what Scotland's total offshore wind capacity could be if the significant offshore wind development was driven not only by the electricity demand sector but also the green hydrogen sector (particularly to export hydrogen to the rest of the UK or Europe).

The target of 75GW by 2050 would take up to as little as 1-2% (around 9000km^2) of the UK's seabed and does not consider the potential for exporting hydrogen, it is a capacity required to meet net-zero targets, so this does not represent a limit to what capacity could be provided by offshore wind but rather a target for decarbonising the UK.

The Scottish Government and Crown Estate Scotland has yet to clarify the number and timings of future offshore wind leasing rounds, aside from a second ScotWind licensing round which will be held two years after the conclusion of the ongoing round. It is anticipated that further seabed areas will need to be identified and made available for development in order meet these goals.

Table 3.2 Offshore wind development scenarios

Capacity scenario	Capacity (GW)	Reasoning
2025		
Ambitious	5.8	Scenario based on the assumption that every offshore wind farm project currently with consent is fully commissioned ahead of 2025.
Planned development	5.4	Scenario based on the assumption that every current offshore wind farm project currently in the pre-construction phase with a financial route to market secured, and certain consented offshore wind farms (Inch Cape and Moray West) that could progress ahead of 2025.
Business as usual	3.4	Scenario based on the assumption that every current offshore wind farm project currently in the pre-construction phase with a financial route to market secured is fully commissioned by 2025.
2032		
Ambitious	20.0	Scenario includes all current offshore wind farms in the pipeline including those in early planning (pre-application), as well as the full potential 10 GW available through ScotWind offshore wind farm licensing.
Planned development	15.0	Scenario includes all current offshore wind farms in the pipeline including those in early planning, as well as approximately 5 GW available from ScotWind, anticipated to be 3 GW of fixed foundation projects and 2 GW of floating wind.

Business as usual	13.0	Scenario includes all current offshore wind farms in the pipeline including those in early planning, as well as approximately 3 GW available from ScotWind, anticipated to be fixed foundation projects that can be progressed on faster timescales.
2045		
Ambitious	60	Estimated capacity that could be achieved if multiple leasing rounds were undertaken ahead of 2045 and development was promoted beyond the current net-zero targets. This value represents around 1/3 of the total practical developable Scottish offshore wind resource as estimated in 2010 by the Offshore Valuation Group.
Planned development	30	Scottish Industry ambitions for targeting 40% of the 75 GW target for offshore wind deployment set by the Committee for Climate Change by 2045
Business as usual	27	Estimated lower industry ambition in line with achieving 30 GW by 2050, 40% of the 75GW target for offshore wind deployment set by the Committee for Climate Change by 2045

Onshore wind also has a significant role to play in the wind energy sector with a current installed capacity of 8.4 GW and an additional 4 GW of capacity consented and a further 4 GW under planning (Scottish Renewables, 2020).

3.2.2 Hydrogen Production from Scotland’s Offshore Wind

Estimating offshore wind capacities deployed in 2025, 2032 and 2045 was a critical step to assess Scotland’s potential for green hydrogen production from offshore wind. The offshore wind projections were then used to calculate the green hydrogen potential in the given year based on each scenario, as shown in Table 3.3.

The green hydrogen potential column shows theoretical production capacities, based on offshore wind deployment. In this assessment, it was assumed that all wind was used for hydrogen production. No attempt has been made within this study to assess the future potential for additional grid connection. This potential was then compared to hydrogen demand (as reported in Section 2.2) to understand how much hydrogen would be required to meet Scotland’s hydrogen demand solely from offshore wind. Table 3.3 provides the key outcomes from Scotland’s hydrogen production and demand assessment, and Figure 3.1 shows the net excess of production potential vs. Scottish demand.

Table 3.3. Hydrogen Production from Offshore Wind in Scotland (2025-2045)

Scenario	Projected offshore wind capacity (GW)	100% offshore wind to green hydrogen potential (GWh/year) [15]	Scotland's hydrogen demand (GWh/year)[16]	Offshore wind capacity required to meet Scotland's hydrogen demand (GW)[17]	Percentage of total wind capacity required for hydrogen demand
2025					
Ambitious	5.8	17,945	1,990	0.64	11%
Planned development	5.4	16,707	1,730	0.56	10%
Business as usual	3.4	10,518	403	0.13	4%
2032					
Ambitious	20.0	65,578	21,786	6.6	33%
Planned development	15.0	49,183	20,356	6.2	41%
Business as usual	13.0	42,620	7,884	2.4	18%
2045					
Ambitious	60	202,142	75,976	22.6	38%
Planned development	30	101,072	65,492	19.4	65%
Business as usual	27	90,964	20,141	6	22%

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[15] Based on the following assumptions: Offshore wind capacity factor = 0.5, hydrogen system availability factor = 0.95, electrolysis efficiency (2025) = 18.87 kg/MWh (IRENA, 2018), electrolysis efficiency (2032) = 20.00 kg/MWh (Hydrogen Europe and Hydrogenics), electrolysis efficiency (2045) = 20.55 kg/MWh (Project Dolphyn).

[16] Equal to Scotland's hydrogen demand projections scenarios assessed in Section 2.2.

[17] Offshore wind capacity required to be solely dedicated to hydrogen production, if Scotland's entire hydrogen demand was to be met.

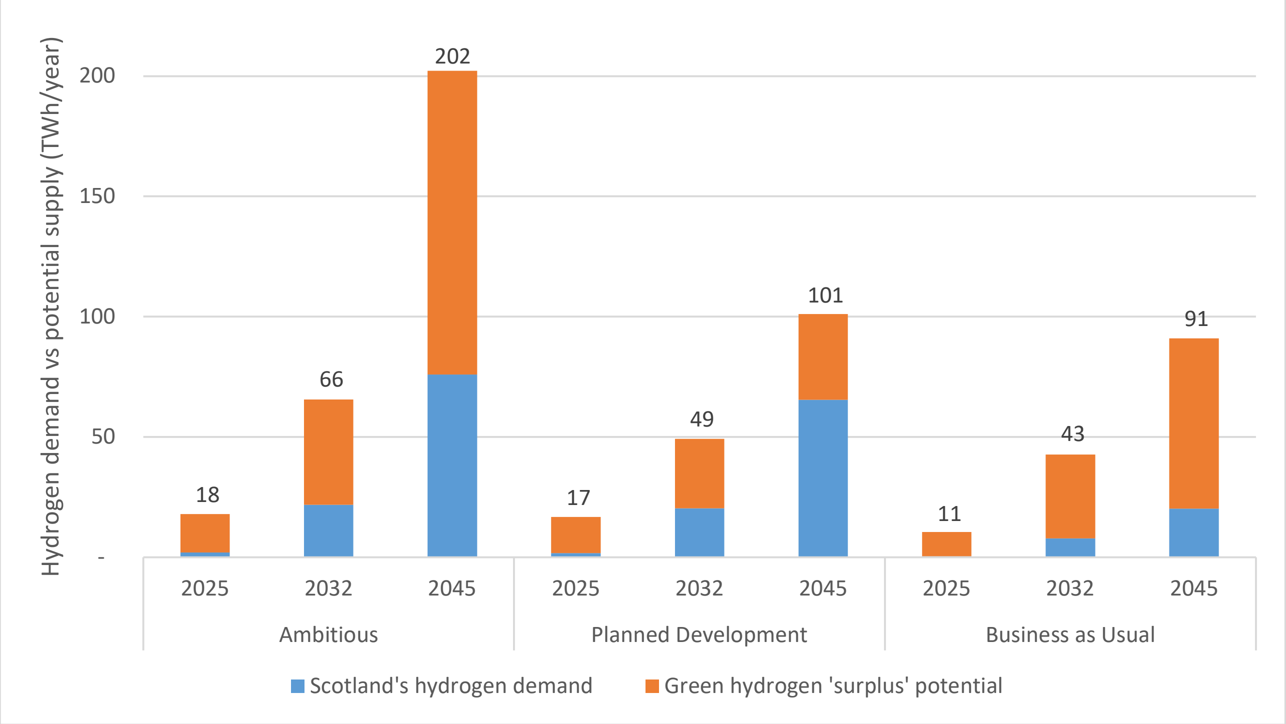


Figure 3.1. Scotland's green hydrogen supply potential vs demand

3.2.3 Scotland’s Net Green Hydrogen Export Projections

Previous hydrogen analyses within this report indicate that green hydrogen produced from Scotland’s offshore wind can exceed Scotland’s hydrogen demand. This is not an unexpected conclusion, since green hydrogen production requires renewable electricity for electrolysis, and Scotland is already a net exporter of renewable electricity. Considering Scotland’s future offshore wind deployment projections and its overall offshore wind resource, it is likely that Scotland’s clean energy export will keep increasing in the next decades.

Although it is likely that Scotland will continue to export renewable electricity generated from offshore wind to the rest of the UK, there are limitations related to electricity grid infrastructure between Scotland’s offshore wind resources and demand centres predominantly based in the south of the country. These substantial grid infrastructure requirements combined with the intermittency and non-dispatchability of offshore wind generation indicate that Scotland’s offshore wind resource can be fully harnessed only if other vector carriers are introduced, such as hydrogen.

This chapter does not aim to estimate the split between electricity export and green hydrogen export but rather indicate how much ‘surplus energy’ could be generated from offshore wind in Scotland and used for domestic (rest of the UK) or international (continental Europe) green hydrogen export. It should be highlighted that realistically, some of this ‘offshore wind energy surplus’ will be exported as electricity, rather than hydrogen only, particularly in 2020s before hydrogen export becomes more mature and cost competitive.

To understand the export opportunity associated with green hydrogen produced from offshore wind, Scotland’s hydrogen supply and demand projections had to be assessed independently. These projections were assessed in Section 2.2.3 (demand) and Section 3.2.2 (supply), and highlighted how much hydrogen will be required in Scotland between 2025 and 2045 (net-zero), and how much green hydrogen could be produced in the same period by harnessing renewable electricity coming from offshore wind generation.

Figure 3.2 compares Scotland’s potential hydrogen supply and demand in medium (2032) to long term (2045). It was assumed that although Scotland’s hydrogen demand in 2025 can be met from green hydrogen, the high costs and technology immaturity of transporting hydrogen over long distances will prevent Scotland to export hydrogen to the rest of the UK or internationally by 2025. There may be some specific cases where green hydrogen produced in Scotland may be transported to Northern England. However, the scale of this opportunity in 2025 is likely to be small, and the vast majority of 'surplus' offshore wind in Scotland will be used to feed into the local electricity grid rather than to produce green hydrogen for export.

The net green hydrogen export opportunity shown in Figure 3.2 was created using the best and the worst-case scenario from export perspective to understand what the opportunity range is. It was assumed that Scotland's future annual net hydrogen demand needs to be met first, and any surplus green hydrogen can then be used for domestic or international export.

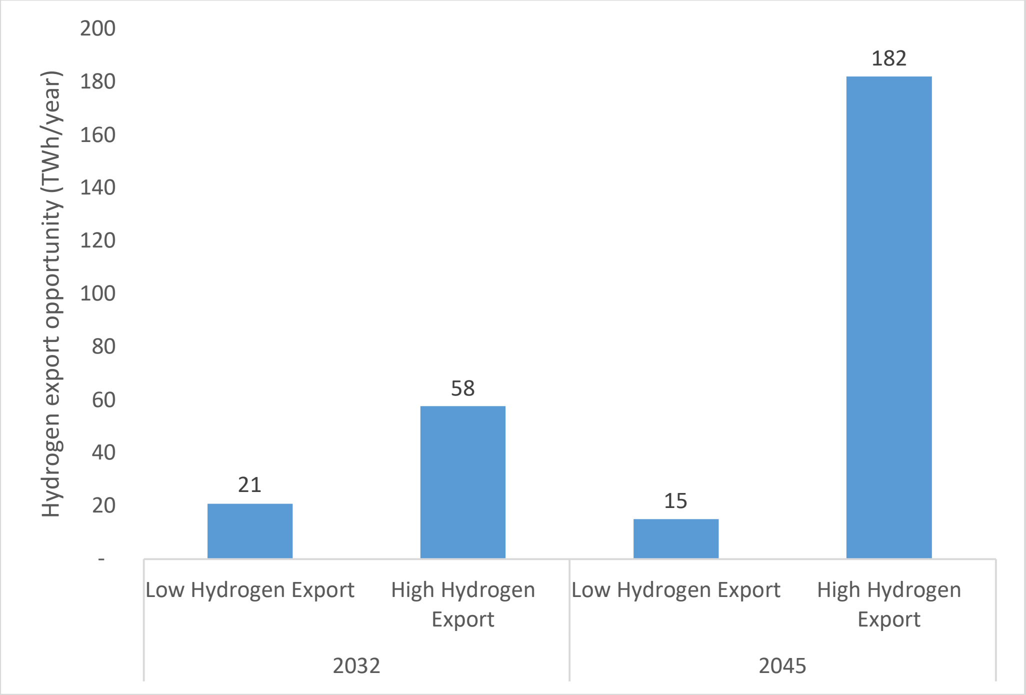


Figure 3.2. Scotland's Net Hydrogen Export Opportunity

The Low Hydrogen Export scenario combined Scotland's most conservative offshore wind generation projections, with the highest demand projections. This resulted in the lowest export opportunity for Scotland, since most of the green hydrogen produced from offshore wind would be used in Scotland, and less would be left for potential domestic or international export.

On the other hand, the High Hydrogen Export scenario assumed the most optimistic offshore wind deployment, and the lowest hydrogen demand uptake in Scotland. This resulted in significantly higher proportion of green hydrogen to be exported to the rest of the UK and continental Europe. The actual hydrogen export opportunity is likely to lie somewhere in between these two scenarios.

2032

The 2032 export scenarios revealed that Scotland's offshore wind will have the capacity to meet Scotland's entire hydrogen demand and export additional 21-58 TWh/year of hydrogen domestically (rest of the UK) or internationally (continental Europe). It should be highlighted that even in the most conservative export scenario with high hydrogen demand and low supply, Scotland's offshore wind will be able to produce significantly more green hydrogen than will be required. This highlights the fact Scotland's abundant offshore wind resources will be at the core of Scotland's energy transition.

Scotland's net hydrogen export opportunity in 2032 is projected to be between 21 and 58 TWh/year. Comparing the former with Scotland's most optimistic hydrogen demand projections for 2032 shows that

Scotland can produce at least twice as much hydrogen as it will be able to use by 2032. Based on the projections discussed in Section 2.2, the rest of the UK will require 42-60 TWh/year and the rest of EU 431-585 TWh/year. This indicates that there is likely to be sufficient hydrogen market by 2032 to uptake all of Scotland's 'surplus' green hydrogen.

To conclude, Scotland's offshore wind could produce 2-8x more hydrogen than it will require by 2032. Although a lot of this offshore wind generation will not be converted into hydrogen bur rather exported as electricity, the potential hydrogen export opportunity is evident.

2045

By 2045, Scotland will be able to produce enough green hydrogen not only to meet its hydrogen demand but also to export to the rest of the UK and continental Europe. The split of domestic versus international export was not assessed within this study. However, it will strongly depend on the cost of transporting this green hydrogen from A to B. Costs associated with hydrogen transport are assessed in Section 4.2.

Scotland will be able to export between 15 and 182 TWh of hydrogen annually. This strengthens the case for green hydrogen production from offshore wind in Scotland. Even when using the most conservative offshore wind deployment projections and the most ambitious hydrogen demand projections, Scotland can still produce more hydrogen than it will require by 2045.

Based on the projections discussed in Section 2.2, the rest of the UK will require 90-624 TWh/year and the rest of EU 668-1,551 TWh/year. This indicates that there is expected to be enough hydrogen demand for Scotland to become a major green hydrogen producer and exporter by 2045 by making the most of its offshore wind resources as well as its legacy of being a net energy exporter.

3.2.4 Summary

From this it can been seen that in all scenarios, it is likely that Scotland will, on a net basis, have potential to produce more hydrogen than can be consumed locally. It is acknowledged that this is an over-simplified picture and that other factors will affect the actual export potential including:

- Intermittency of offshore wind and resultant green hydrogen and the need to factor hydrogen storage and/or import into the overall system design. To ensure sufficient dispatchable hydrogen it is even possible that hydrogen import may at time be needed and be more cost effective than storage.
- The opportunity, at least in the medium term, for blue hydrogen to produce additional Scottish hydrogen and thereby increase the overall export opportunity.
- The likely continuance of some additional wind to directly generate electrical power into the UK electricity grid. Actual production of green hydrogen may therefore likely be lower than the theoretical production figures presented in this analysis.

Further study would be required to consider these factors in more detail. However, the overarching conclusion that Scotland likely has opportunity to be a net exporter of hydrogen is considered valid.

3.3 Scotland's Existing Infrastructure

The extensive physical infrastructure existing principally due to Scotland's well-established oil and gas sector presents several opportunities to facilitate in particular the export of hydrogen either to Europe or worldwide.

In this section we make a preliminary assessment of pipelines, ports and terminals that could be repurposed for green hydrogen export. Offshore oil platforms could also potentially be repurposed for offshore green hydrogen production but as these would be specific to individual wind farm developments they have not been considered in detail in this initial study.

This section also presents a high-level overview of the potential modes of ship-based export of hydrogen, including via conversion to ammonia or Liquid Organic Hydrogen Carrier (LOHC)

3.3.1 Pipeline Infrastructure

Figure 3.3 shows the existing Scottish oil and gas pipeline and terminal infrastructure, overlaying the existing offshore wind farms and currently planned (ScotWind Leasing round) further development areas.

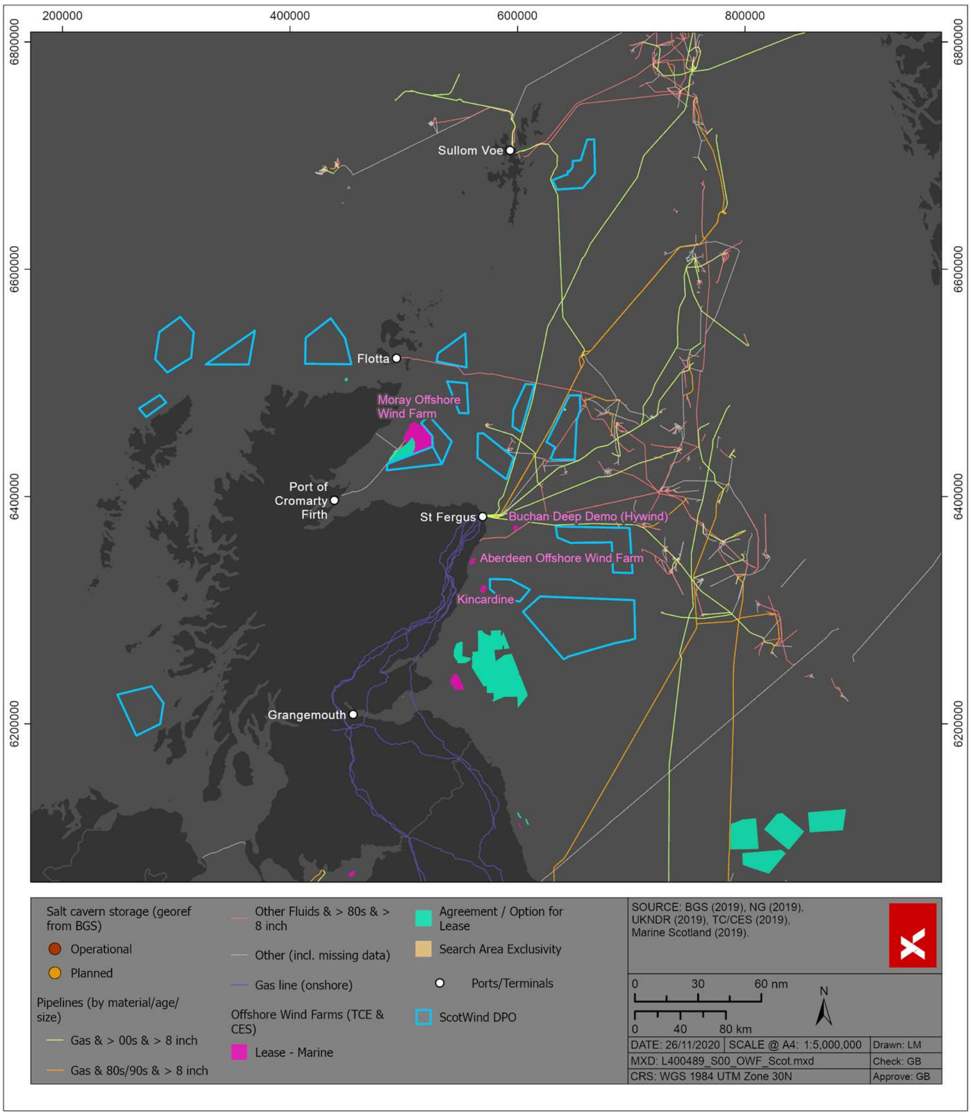


Figure 3.3: Scottish Offshore Oil and Gas Infrastructure

Figure 3.4 shows the extension of this infrastructure to England and to continental Europe via interconnector pipelines at Bacton.

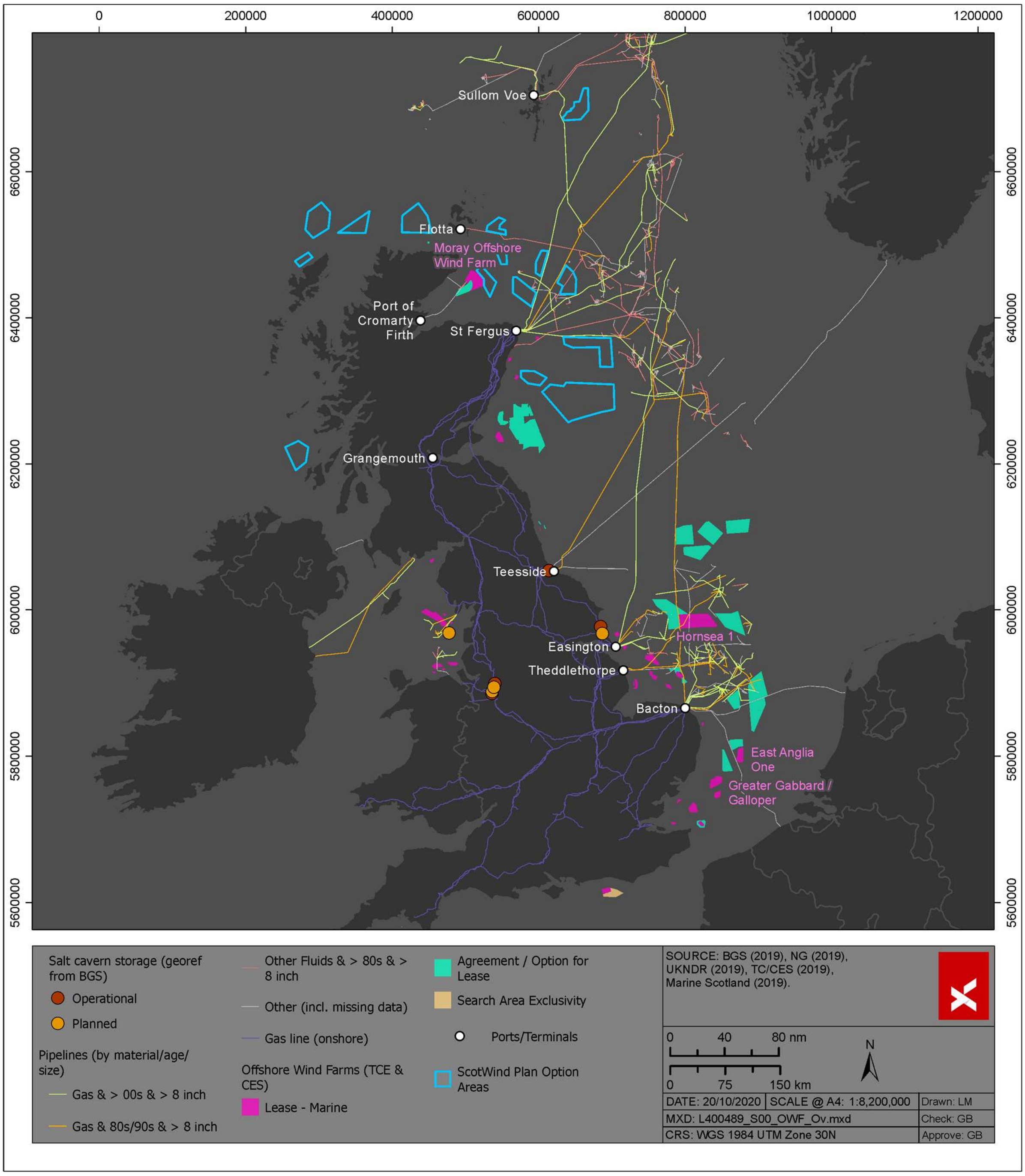


Figure 3.4: Scottish pipeline connections to England and Europe.

There are currently four pipelines, which run from the European continent to the British mainland:

- The UK-Belgium interconnector (IUK): This pipeline runs between Bacton in Norfolk and Zeebrugge in Belgium and connects Britain to the mainland Europe gas network. This pipeline has an import capacity of 25.5 billion cubic metres (bcm) a year. It is the only pipeline that currently operates bi-directionally, meaning it can both import gas to Britain as well as export gas to mainland Europe. The direction of flow depends on supply and demand and relative prices.
- The UK – Netherlands pipeline (BBL): This runs from Balgzand to Bacton in Norfolk. This pipeline has an import capacity of 14.2 bcm a year.
- The Vesterled pipeline link: This pipeline connects St Fergus in Scotland to a number of Norwegian gas fields. This pipeline has a capacity of 14.2bcm a year.
- The Langeled pipeline: At the time of its commissioning in 2006 this pipeline, which runs from Nyhamna in Norway to Easington in Yorkshire, became the longest underwater gas pipeline in the world at 1,200km. The pipeline has a capacity of 26.3 bcm

In terms of exporting hydrogen to the northern European demand hubs highlighted in Section 2, Scotland therefore has opportunity to export both via England and via Norway. Export via Bacton potentially brings synergy with export of blue and green hydrogen produced from the southern North Sea gas fields and offshore wind farms. Scottish hydrogen could potentially be transported to Bacton via the existing 34” SEAL (Shearwater to Bacton) pipeline, which in turn could be connected to St. Fergus through repurposing of (and reversing flow in) the 20” Fulmar to St. Fergus gas pipeline.

Hydrogen introduced into the Langeled pipeline to Easington could potentially be redirected to Bacton via relatively short new interconnections between gas pipelines currently running from southern gas fields to both terminals. This could also serve as an export route for hydrogen produced from the Humber Net Zero hub. Similarly, repurposing of the existing CATS gas pipeline into Teesside could have synergies with hydrogen produced from that planned industrial decarbonisation hub.

It is beyond the scope of this initial study to examine in detail these multitude potential opportunities for pipeline repurposing. It is clear however, that they need to be considered in the context of an integrated UK-wide (or indeed European) hydrogen transportation plan, as also highlighted in the recent ORE Catapult report.

Xodus has previously performed a study for the Oil & Gas Technology Centre (OGTC) considering the repurposing of UK oil and gas pipelines for both hydrogen and CO_2 transport, including examining some of the technical consideration associated with such a change of service. The conclusions of that study are summarised as follows:

- Oil and gas pipelines have been converted to hydrogen service before, and the conversion of subsea pipelines is possible if the pipeline meets the material and dimensional requirements for safe operation. Not all pipelines will meet these requirements or will be too damaged for safe operation. Novel technologies such as polymer liners have been explored to make unsuitable lines compatible to hydrogen service. Installation of polymer liners on subsea pipelines for hydrogen service is technically challenging and requires additional research to establish technical and economic feasibility.
- Hydrogen service causes embrittlement of materials: a reduction in yield strength and fracture toughness and an increased crack growth rate, leading to reduced fatigue life.
- Hydrogen embrittlement is dependent on operating conditions and material properties and has a greater effect on steels with higher tensile strength.
- The recommended pipeline material grades for hydrogen service are API X42 and X52. Grades above X52 are more likely to be severely affected by hydrogen embrittlement.
- The hydrogen maximum operating pressure should be defined so that the maximum stress in the pipeline walls is below 30-50% of the minimum specified yield strength.

- The limitations of stress and material grade equates to approximately 50 – 150bar maximum pressures for typical sizes of X52 pipelines which appears feasible for hydrogen storage and transportation at this stage.
- Detailed data on material specifications or operating pressures and temperatures of subsea oil and gas pipelines is not readily available. It is however more likely for older pipelines to be of a lower material grade (X42 or X52). Pipelines from the '90s were identified as optimum as they are likely to still have acceptable mechanical integrity and old enough to have a lower yield strength.
- For pipelines that are considered incompatible with hydrogen service due to material compatibility, novel technologies could be developed to overcome material challenges. Polymer liners are currently installed in subsea pipeline, though it is already technically challenging to retrofit them on existing pipelines. Significant advancements in liner technology would be required to ensure compatibility with hydrogen service. Currently no liner can prevent permeation of hydrogen, due to its small atomic size, and therefore a liner will not prevent hydrogen embrittlement. A suitably designed venting system would also likely be required to avoid gas build up in the annulus between the liner and the steel, that would cause liner collapse in case of depressurisation.

Beyond (or possibly to interconnect) existing pipeline infrastructure, it will be possible to build new hydrogen pipelines to export hydrogen from Scotland.

Currently there are circa 4,500km of hydrogen pipelines worldwide, operators are mainly large industrial gas producers such as Air Liquide, Air Products and Chemicals, Praxair, etc. Pipe sizes typically between 8-in & 12-in with design pressures typically in the range 40 to 60 bar (Oil&GasStatistics, 2020).

Pipelines are typically made of carbon steel (API 5L or ASTM-specified grades). There are approximately 40 km of hydrogen pipelines within the UK and 1500 km across mainland Europe. However, these pipelines are primarily for distribution purposes as oppose larger transmission pipelines such as those in the US.

To transport hydrogen gas through a newly installed pipeline system the same considerations discussed in the previous section regarding material selection apply. The manufacturers and installation companies needed are exactly the same as those already supplying and installing natural gas pipelines and infrastructure.

Other potential solutions include using fibre reinforced polymer (FRP) pipelines for hydrogen distribution. Xodus is aware of one FRP pipe manufacturer, which has successfully qualified one of their pipe grades for hydrogen service.

Whilst the far offshore of Scotland is heavily congested with existing pipelines, Figure 3.5 (source : NPD) shows that south of St. Fergus there is a very low density of existing pipelines (other than the interconnector lines already mentioned above) , which would enable a relatively unencumbered route towards northern continental Europe.

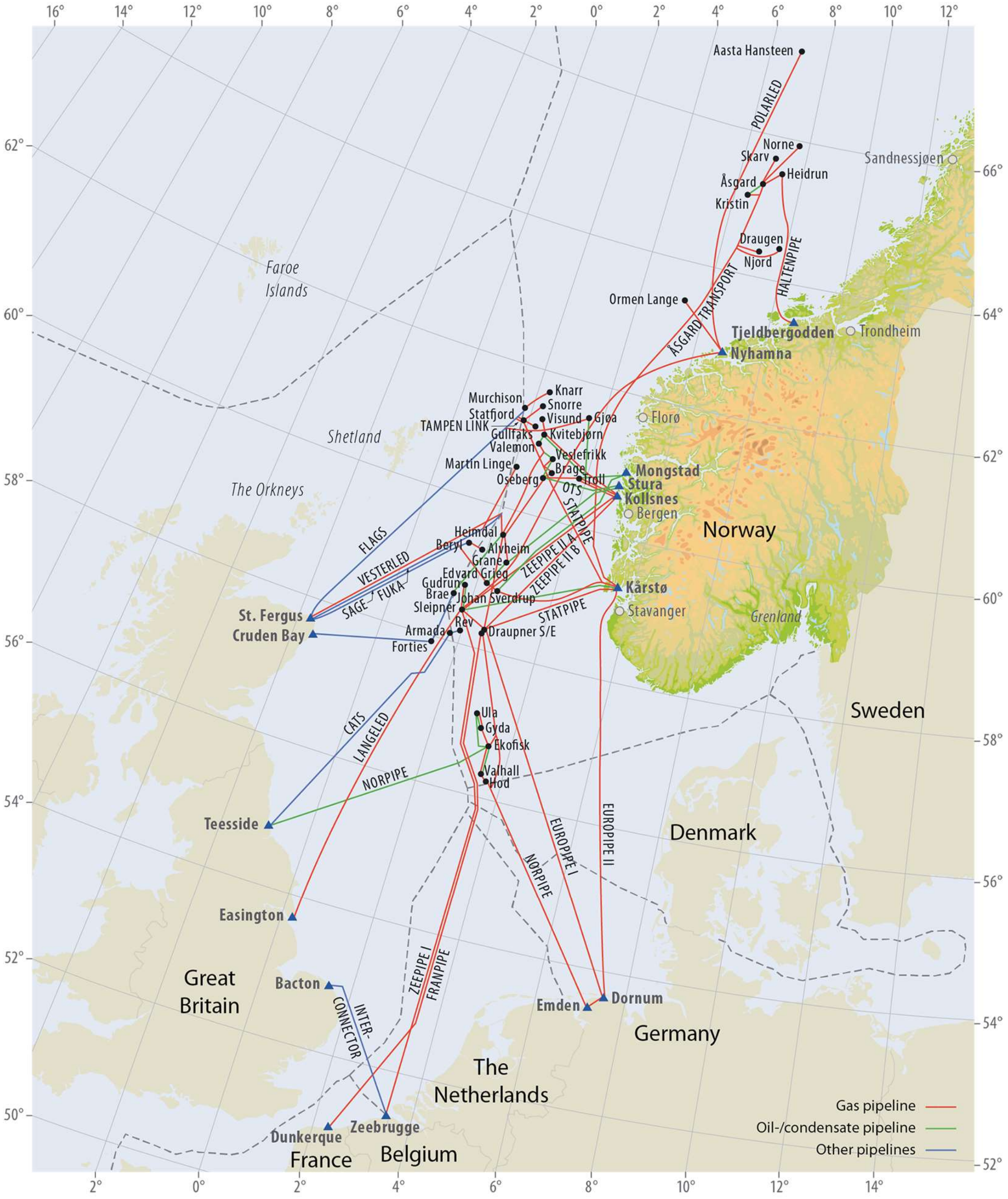


Figure 3.5: Trans-Europe Pipeline Network

More significant constraint is likely encountered landing new pipelines in northern Europe. The tidal mudflats along much of the coastline from northern Netherlands to Denmark, which collectively form the Wadden Sea, are inscribed as a UNESCO World Heritage Site and contain several Ramsar protected areas, is indicated in Figure 3.6.

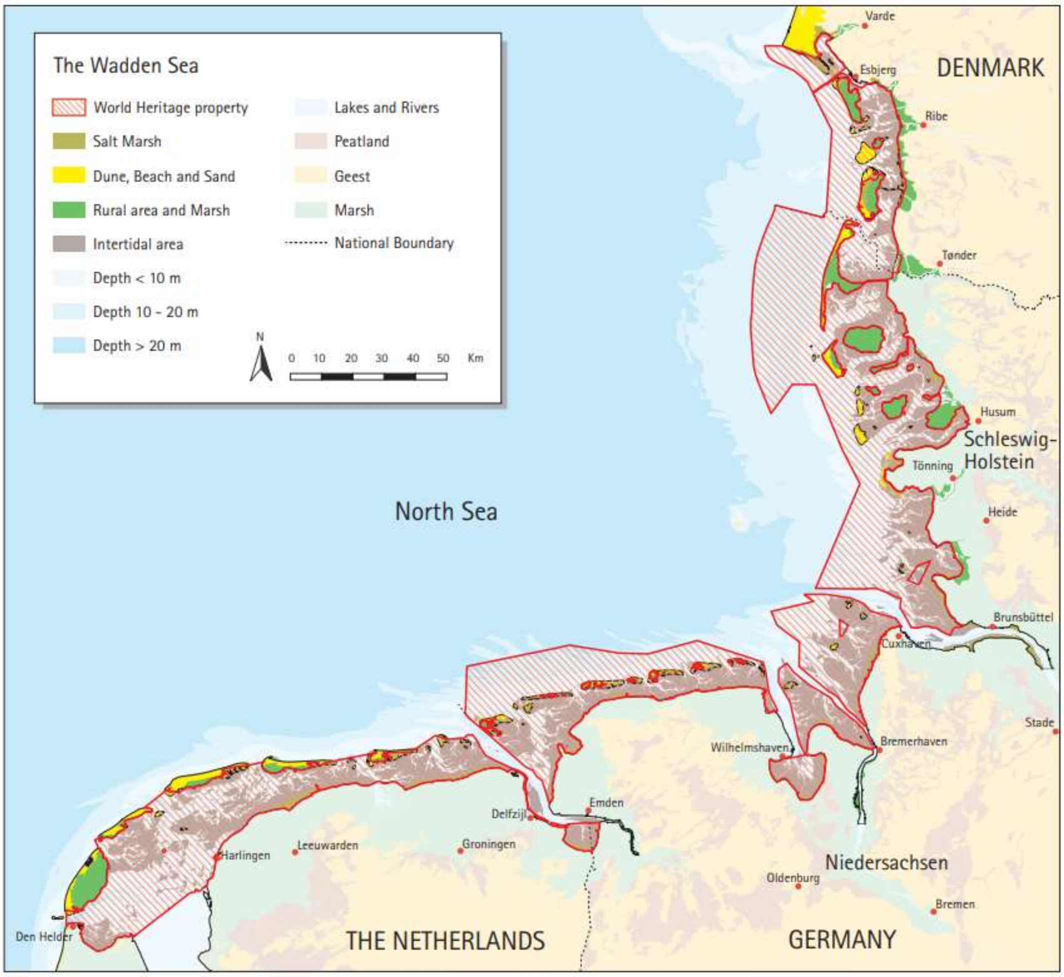


Figure 3.6: Wadden Sea World Heritage Site

This will constrain potential landing points, other than possibly if following existing corridors into Emden or Dornum and will perhaps most likely drive the landing point south to Den Helder. Here though, a dense infrastructure of Dutch offshore gas platforms and pipeline is encountered, similar to that on the UK side of the Southern North Sea. More work would be needed to identify feasible and consentable new pipeline routes from Scotland to northern Europe.

With a single supply directly to mainline Europe would give rise to the issue of security of supply, linking within a regional network offshore and on land within Europe may avoid this and increases the number of tie-in locations within the hubs.

In summary, Scotland has both multiple potential opportunities to export hydrogen to the rest of the UK and to Europe via repurposed oil and gas pipelines. There is good corridor for a new pipeline direct to Europe, but constraints on landing point would need careful consideration.

3.3.2 Ship-Based Hydrogen Export

Scotland has a number of major oil terminals and ports that could be redeveloped for the ship-based export of hydrogen. However, the majority of hydrogen used worldwide today is produced near to the point of consumption, which means that hydrogen is not commonly a globally transported commodity. Therefore, before considering specific terminals and ports, it is useful to introduce the four principal technologies currently proposed for such export, as features of these technologies will be important when considering the potential attractiveness of an existing site.

3.3.2.1 Liquified Hydrogen

Whilst natural gas is commonly transported in liquefied form (LNG), this is less feasible for hydrogen due to the far lower boiling point of hydrogen; where natural gas typically liquifies at -160 deg.C, hydrogen requires -253 deg.C which is only 20 deg.C above absolute zero. This introduces exotic material and cryogenic risk issues and results in high cooling energy demand. Therefore, historically liquified hydrogen has only been used in niche and small-scale applications.

A notable development in relation to bulk ship transportation of liquified hydrogen is the Hydrogen Energy Supply Chain (HESC) pilot project to ship hydrogen from Australia to Japan (HESC, 2020). The newly built 116m long Suiso Frontier Liquified Hydrogen Carrier ship, built by Kawasaki Heavy Industries, contains 1,250 m^3 of cryogenic storage.

Figure 3.7: Suiso Frontier LHC (image from HESC)

3.3.2.2 Ammonia

Ammonia is easier to transport than hydrogen or LNG as it can be turned into liquid at temperatures of -33°C or a pressure above 10 bar. This is a very similar pressure/temperature range to LPG and the same vessels are commonly used. Ammonia shipping is already a very well-established global operation.

Vessel capacity spans a wide range from small carriers generally utilising pressurisation rather than refrigeration, through to Very Large Gas Carriers (VLGC). Larger vessels use refrigeration or semi-refrigeration for storage. Typical vessel capacities and dimensions are shown in Table 3.4, and Figure 3.8 shows a typical VLGC.

Table 3.4: Typical Gas/Ammonia Carrier Dimensions

Carrier Type	Type	NH_3 or LPG Volumetric Capacity (k m3)	Length (m)	Beam (m)	Draft (m)
Very Large Gas Carrier (VLGC)	Refrigerated	60 – 100	230 - 300	35 - 40	12
Large Gas Carrier (LGC)	Refrigerated	40 – 60	200	32	12
Mid Gas Carrier (MGC)	Refrigerated	25 – 40			
Handysize Gas Carrier	Semi Refrigerated	15 – 25			
Small Gas Carrier	Semi-Refrigerated	5 – 15	100	25	12
Small Gas Carrier	Pressurised	< 5			

Figure 3.8: Typical VLGC

Ammonia is conventionally produced from natural gas via the integration of steam methane reforming (to produce hydrogen) and the Haber-Bosch process to catalytically combine hydrogen with nitrogen separated from air. Globally, this process is currently used to produce 150 million te of ammonia per year, mostly for use as fertiliser. Without carbon capture and storage (CCS), it is estimated that the Haber-Bosch process is responsible for about 1.2% of all man-made carbon emissions.

However, for ammonia production from green hydrogen, a far simplified process is required, as illustrated in Figure 3.9. The air separation and core Haber-Bosch reactor are retained, but the stream reforming and methanation stages are removed. In a greenfield context, the whole system lends itself to electrification.

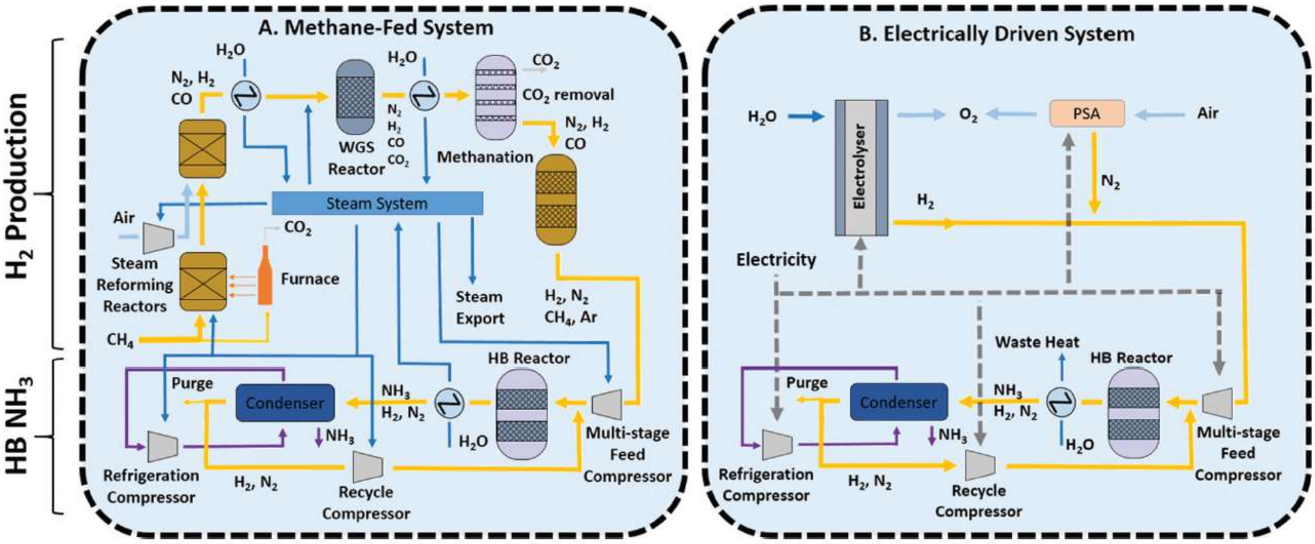


Figure 3.9: Comparison of SMR and Green Hydrogen Ammonia Process (Smith, Hil, & Torrente-Murciano, 2020)

A key difference between ammonia and LOHC (see Section 3.3.2.3) is that ammonia can (and most likely will) be used directly, either as fertiliser feedstock or as direct fuel. Indeed, there are today no known industrial scale processes to decompose (‘crack’) ammonia back to hydrogen. A recent study (Ecuity, 2020) has assessed various potential technologies and it has been estimated by the UK Committee on Climate Change that the energy loss turning ammonia back into hydrogen would be around 15 – 25 % (Committee on Climate Change, 2018).

3.3.2.3 *Liquid Organic Hydrogen Carriers (LOHC)*

Just as ammonia improves the transportability of hydrogen by combining it chemically with nitrogen to make a compound which is liquid a higher temperature, so LOHC refers generally to the chemically combining of hydrogen (‘hydrogenation’) with a carrier organic compound for transportation, and then chemically decomposing (“de-hydrogenation”) to regenerate hydrogen and the original carrier compound, which is then shipped back for re-use. A basic premise of LOHC is that the hydrogenated product is a liquid at ambient temperature, this enabling the use of conventional bulk liquid tanker (rather than the refrigerated or pressurised carriers used for ammonia)

Many different chemicals are currently under active consideration for LOHC, including:

- Methyl Cyclohexane (MCH). Chiyoda Corporation have developed and successfully demonstrated the SPERA Hydrogen® system using MCH (hydrogenated form of toluene) (Chiyoda Corporation, 2017). In May 2020, a pilot plant generating $50m^3/h$ MCH successfully commenced supply of hydrogen transported by sea from Brunei Darussalam by sea to Japan. This may be considered the currently most advanced LOHC process.

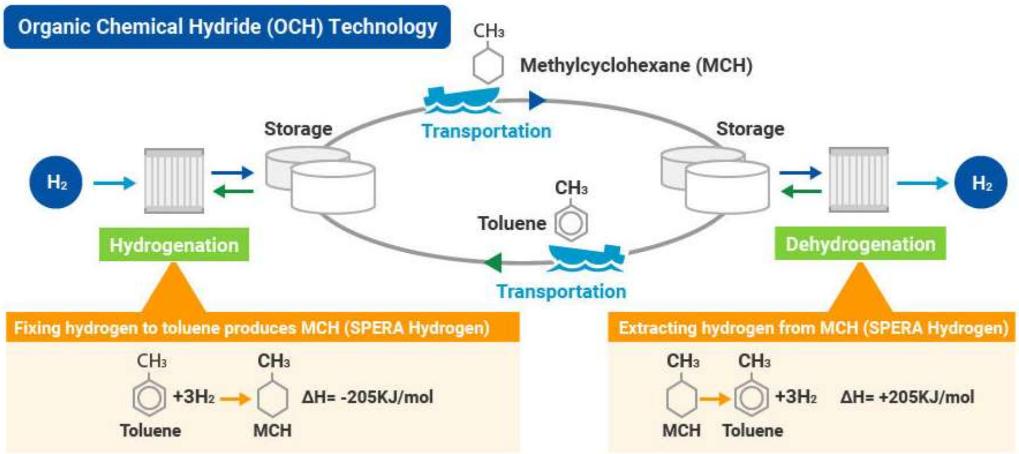


Figure 3.10: Chiyoda SPERA Hydrogen® Process

- Di-benzyltoluene
- N-ethylcarbazole
- Di-cyclohexylmethane (DCHM)

In all cases the hydrogenation step is highly exothermic (giving out heat) and the de-hydrogenation step highly endothermic (requiring heat). LOHC could provide a safe and lighter weight option for hydrogen transportation. As the technology is relatively new, several factors will need to be explored before these can be viable options. The LOHC must have a high recovery yield of both hydrogen and the carrier and the carrier must be robust enough to endure multiple cycling.

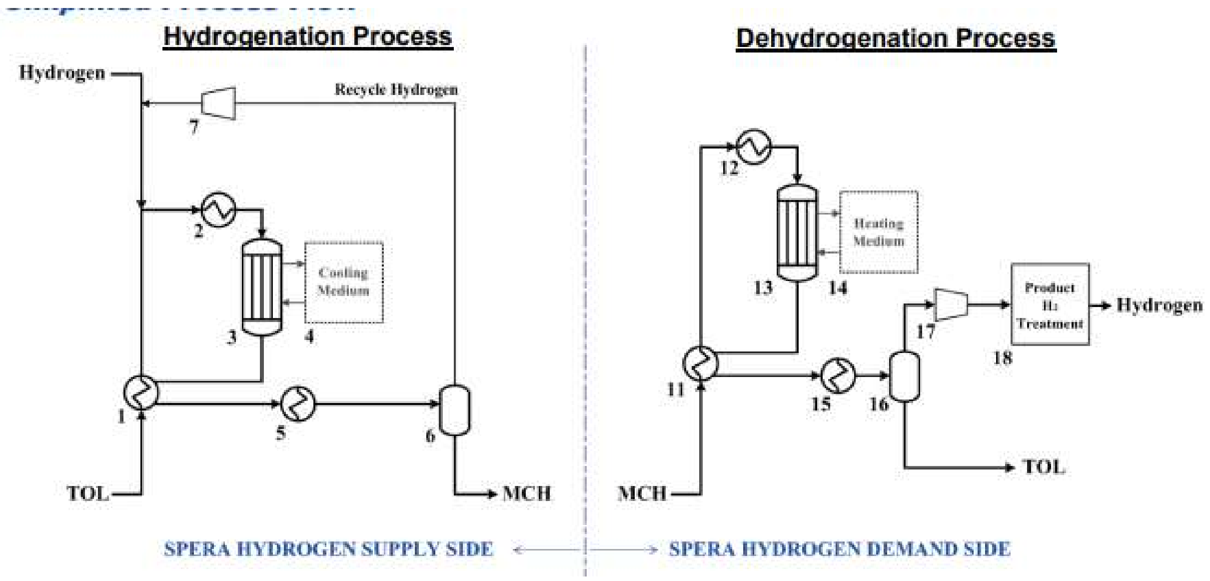


Figure 3.11: Chiyoda SPERA Hydrogen® Process Flow Diagram

3.3.2.4 *Compressed Hydrogen*

Ship transportation by compression alone (rather than liquefaction) has not generally been proposed for hydrogen due to the ultra-high pressures required or relatively low energy storage density achieved at conventional pressures proposed for the compressed transportation of natural gas (CNG). However, and for completeness, it is noted that Global Energy Ventures (GEV) have announced plans to develop a compressed hydrogen ship (H2 Ship) capable of carrying up to 2,000 te of hydrogen, targeted at the Australian market (GEV, 2020).

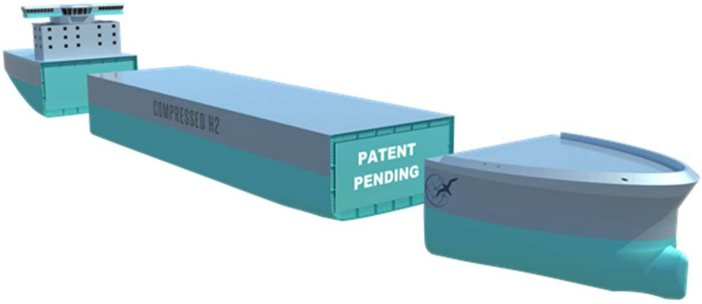


Figure 3.12: GEV H2 Ship Concept

Comparative analysis of these four technologies is beyond the scope of this study, though the following broad observations may be made:

- Shipping of ammonia is already well proven whereas liquified/compressed hydrogen, LOHC technologies are currently immature. Saudi Arabia and Japan are moving forward with plans for transportation of green hydrogen via ammonia.
- Whilst inherently simpler than chemical conversion, both liquified and compressed hydrogen concepts are likely to encounter significant cryogenic risk and metallurgical challenges.
- Conversion of hydrogen to an LOHC (or ammonia) and back to hydrogen consumes additional energy which reduces the overall energy efficiency from wind turbine to consumer.
- Due to the requirement for regeneration and return, LOHC is only suitable for fixed point to point applications (such as the SPERA trial), rather than as a means for distribution of hydrogen. A relatively high cycling frequency is also likely to be needed to amortise the cost of LOH production and regeneration and therefore LOH is not well suited to long distance transportation

For the purposes of cost modelling in Section 4, only ammonia has been considered as there are well established cost benchmarks both for ammonia production and shipping, albeit cost of ammonia production without integration with SMR is less well established.

3.3.3 Terminals and Ports

Scotland possesses multiple existing oil and gas terminals and ports that could be repurposed for hydrogen export. As illustrated in the previous section, all technologies for hydrogen export will require some degree of pre-treatment of hydrogen; in the case of ammonia and LOHC this pre-treatment for chemical conversion is significant. Hence, so long as suitably located, existing industrial sites with similar processes may have an inherent advantage over greenfield sites. Evolution to include hydrogen export may also extend the economic lifetime of existing hydrocarbon terminals. This opportunity has already been recognised by several terminals and various studies have been initiated, as is acknowledged in the following sections.

3.3.3.1 Sullom Voe

The Sullom Voe terminal on Shetland is the most northerly of Scottish terminals and has been in operation since 1978. Fed from oil fields both east and west of Shetland, it is anticipated to remain in hydrocarbon production through to 2045 (and beyond).

Figure 3.13: Sullom Voe Terminal (image: Pearl ES group)

A consortium, including Shetlands Islands Council (SIC), the OGTC and with representatives from regional major offshore oil companies, has recently initiated the ORION Project which envisages the wholescale transformation of Sullom Voe, to include electrification of offshore oil production and generation of both blue (with carbon sequestered in depleted East of Shetland oil fields) and green hydrogen. With limited mainland grid interconnection (Ofgem approval has only recently been granted for a 600 MW interconnector), green hydrogen production and export is a potential key enabler for either future regional offshore wind development or the estimated up to 1 GW of onshore wind potential on Shetland.

Figure 3.14: Sullom Voe Jetty (image: NIRAS)

Sullom Voe has four existing tanker loading jetties; three are designed for crude oil export in tankers up to 350 DWT. The fourth is designed for oil and LPG export in tankers up to 80,000 m3 (mid-range VLGC). The similarity between LPG and NH_3 export suggests the fourth jetty would also be suitable for ammonia export. The clear area around the terminal likely easily sufficient to accommodate any enlarged safety zoning and separation distances required for the production and handling of hydrogen and ammonia.

Sullom Voe is uniquely well-positioned to enable the development of the most extreme northerly of Scotland’s offshore wind resources which might otherwise be stranded if reliant on mainland grid connection. Whilst relatively isolated from existing UK hydrocarbon pipeline network, it is close to existing Norwegian pipeline infrastructure which may provide alternative hydrogen export routes towards northern Europe. The extensive terminal could also be used for direct refuelling of hydrogen-powered ships.

3.3.3.2 Flotta

The Flotta Terminal is located on the island of Flotta in the Orkney Islands just north of mainland Scotland. It was commissioned in 1977, with Repsol Sinopec Resources UK Limited becoming the major shareholder and operator in May 2000. The terminal covers a 395-acre site, approximately one sixth of the area of Flotta Island.

Crude oil is imported to the Flotta Oil Terminal from several offshore installations in the Flotta Catchment Area through a 210km 30” subsea pipeline.

Figure 3.15: Flotta Terminal

The Terminal includes a 'T' shaped jetty capable of handling either crude oil or LPG, situated on the north coast of Flotta. The minimum depth of water alongside is 20.12m and vessels of up to 170,000 tonnes DWT can be handled there.

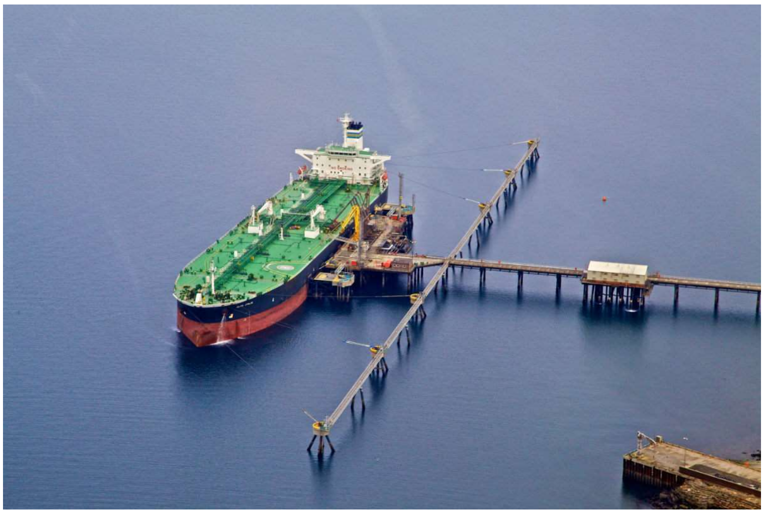


Figure 3.16: Flotta Loading Jetty

Similar to Shetland, Orkney has recently obtained approval for a 220 MW interconnector to the Scottish mainland, also largely premised on enabling future offshore wind generation. Production and export of green hydrogen from Orkney would similarly diversify and potentially enable further offshore wind development.

Similar too to Sullom Voe, the Flotta Terminal:

- is located remotely, making it well able to accommodate any increased safety separation distances.
- Potentially able to provide a refuelling location for hydrogen-powered shipping.

Flotta is the proposed location of the Hydrogen Hub Orkney (H^2O) test facility which forms part of the Hydrogen Offshore Project (HOP), Conducted as part of the BEIS Hydrogen Supply Programme, and with project partners comprising Aquatera, Cranfield University, Doosan Babcock, European Marine Energy Centre (EMEC), National Oilwell Varco (NOV) and The Oil and Gas Technology Centre (OGTC), the HOP project explores various opportunities for offshore hydrogen production by re-using existing oil & gas infrastructure.

3.3.3.3 *Port of Cromarty Firth*

Continuing south, the Port of Cromarty Firth is already a major staging post for the Scottish offshore wind industry, building on a long history of construction and service provision for the offshore oil and gas sector.

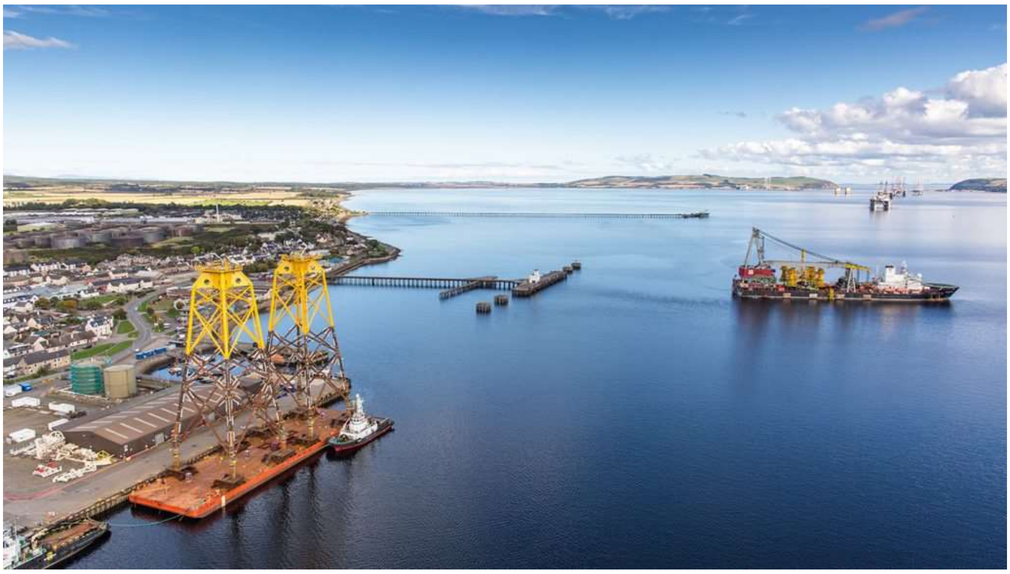


Figure 3.17: Port of Cromarty Firth

With support from HIE, the Highland Council and OGTC the consortium Opportunity Cromarty Firth has been formed specifically to advance plans for green hydrogen production, use and export (including LOH and liquefaction) and with the ambition to become a Free Trade Zone (Opportunity Cromarty Firth, 2020).

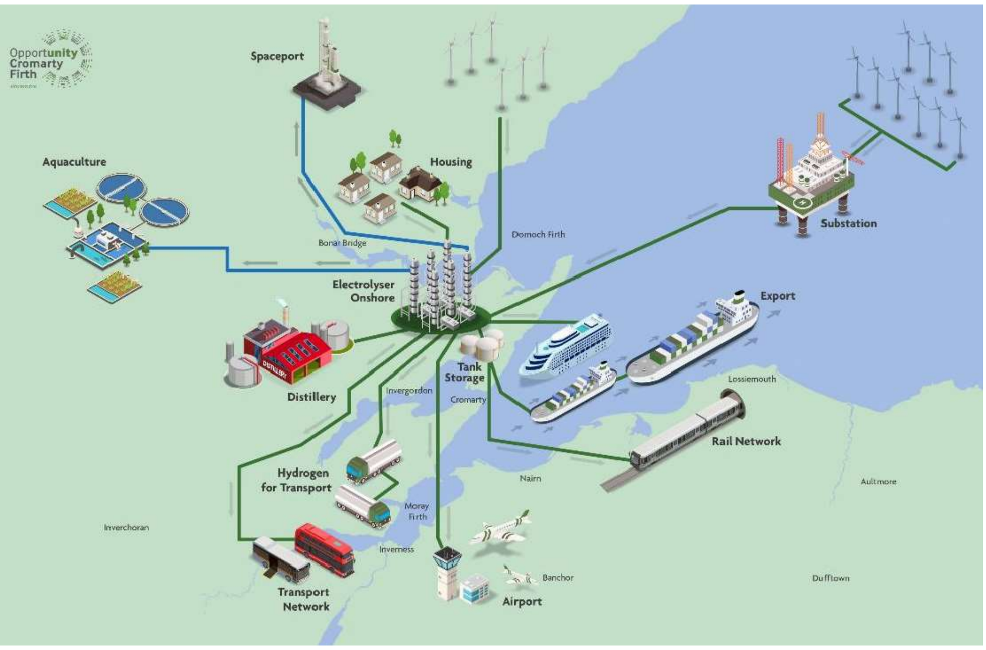


Figure 3.18: Opportunity Cromarty Firth Master Plan

The Port of Cromarty Firth is home to 6 key marine facilities, including the Nigg Energy Park and Oil Terminal. Combined, these facilities provide over 2,000m of quayside in water depth up to 14m and sheltered anchorage in up to 30m water depth.

The Port of Cromarty Firth is well positioned for the multiple North East ScotWind option areas

3.3.3.4 Outer Hebrides Hydrogen Hub

Similar to Orkney, the Outer Hebrides have been developing a green hydrogen strategy and trialling green hydrogen production and use, including the H2seed and H2growth projects, since 2010. In 2019 the Outer Hebrides Local Energy Hub (OHLEH) included green hydrogen generated from a power-from-waste project. The Comhairle nan Eilean Siar (CnES) is currently planning further green hydrogen expansion as part of its updated Energy Strategy.

Stornoway Port and the associated BiFab facilities at Anish Point provide over 600m of quayside, though being in a water depth of only 6m would currently make them unsuitable for LPG/NH3 gas carrier vessels. The current Stornoway Port Masterplan includes the development of a 400m quayside, 10m depth deep-water port adjacent to Anish Point, as shown in Figure 3.19.

Stornoway is well placed for the northerly ScotWind option areas.

Figure 3.19: Stornoway Port Masterplan (artists impression)

3.3.3.5 St. Fergus Gas Terminal

The St. Fergus Gas Terminal approximately 65 km north of Aberdeen was opened in October 1982 and remains the central gathering hub for Northern North Sea gas production. The plant receives gas through the SEGAL (Shell Esso Gas and Associated Liquids) system. This includes wet gas transported through the FLAGS (Far North Liquids and Associated Gas System) pipeline and from the Central North Sea through the Fulmar Gas Pipeline. It also receives gas from Norway through the Tampen pipeline, which connects the Norwegian gas transport system to the FLAGS system.

St. Fergus is thus potentially optimally positioned to receive hydrogen generated offshore and transported to shore through existing gas pipelines. It is also likely the primary candidate for any new hydrogen export pipeline to Europe.

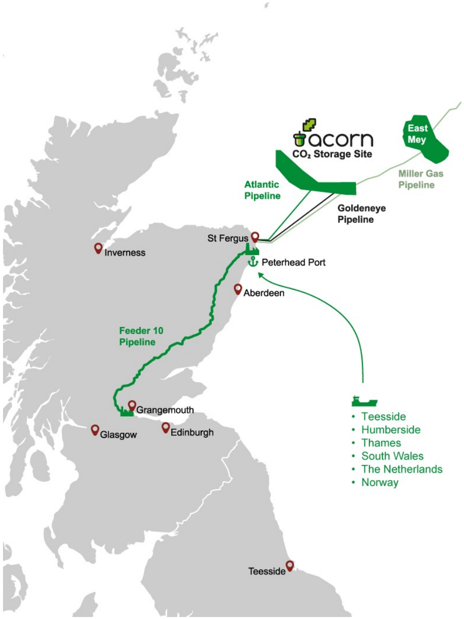


Figure 3.20: Acorn Project

St. Fergus is the focus of the Acorn CCS project, being developed by Pale Blu Dot Energy (Acorn, 2020). Whilst initially targeting capture and storage of CO2 emissions from the St. Fergus Gas Terminal, the project then plans to produce blue hydrogen from gas landed at St. Fergus. Hydrogen produced from Acorn is envisaged to supply a domestic market, as part of the "Hydrogen Coast" initiative. No export of hydrogen is currently planned from Acorn; the nearby port at Peterhead is envisaged only to receive CO_2 imports from elsewhere.

St. Fergus lacks any deepwater port of its own. Peterhead port is a key oil and gas supply base (including decommissioning). Whilst theoretically capable of receiving ships up to 280m in length (and therefore all but the largest VLGC), the extensive other port activities and close vicinity of nearby Peterhead town do not obviously commend Peterhead for hydrogen (or ammonia/LOHC) production and export, certainly in comparison with the previously discussed sites.

Figure 3.21: Peterhead Port

3.3.3.6 Grangemouth/Hound Point

With its extensive existing petrochemicals manufacturing capability, the Petroineos-operated Grangemouth refinery is potentially best suited of all the considered sites for production of ammonia or LOHC. The plant exports oil via the Hound Point marine terminal, which initial appears also suitable for loading of VLGC.

Figure 3.22: Hound Point

Petroineos' published "Grangemouth Renaissance" plan (INEOS, 2020) contains no mention of potential hydrogen export, though most recently a subsidiary of Singapore's LNG9 company has announced plans for a blue hydrogen and CCS project (seemingly similar to Acorn) in the vicinity of Grangemouth (The Falkirk Herald, 2020).

3.3.3.7 Other Sites

The sites listed above are considered to likely represent the most promising candidates for export of Scottish green hydrogen. Other sites, though not excluded, may suffer from several disadvantages, including:

- Size. Many small ports will lack the minimum quayside depth or LOA to accommodate the size of hydrogen/ammonia carrier required for commercial export operation. These smaller ports are perhaps also likely to be close to built-up areas and have busy commercial operations, potentially leading to increased safety issues.
- Location. Ports such a Hunterston and Greenock on the west coast of Scotland are distant from the wind resource and poorly positioned for European export.

3.3.4 Subsurface Hydrogen Storage

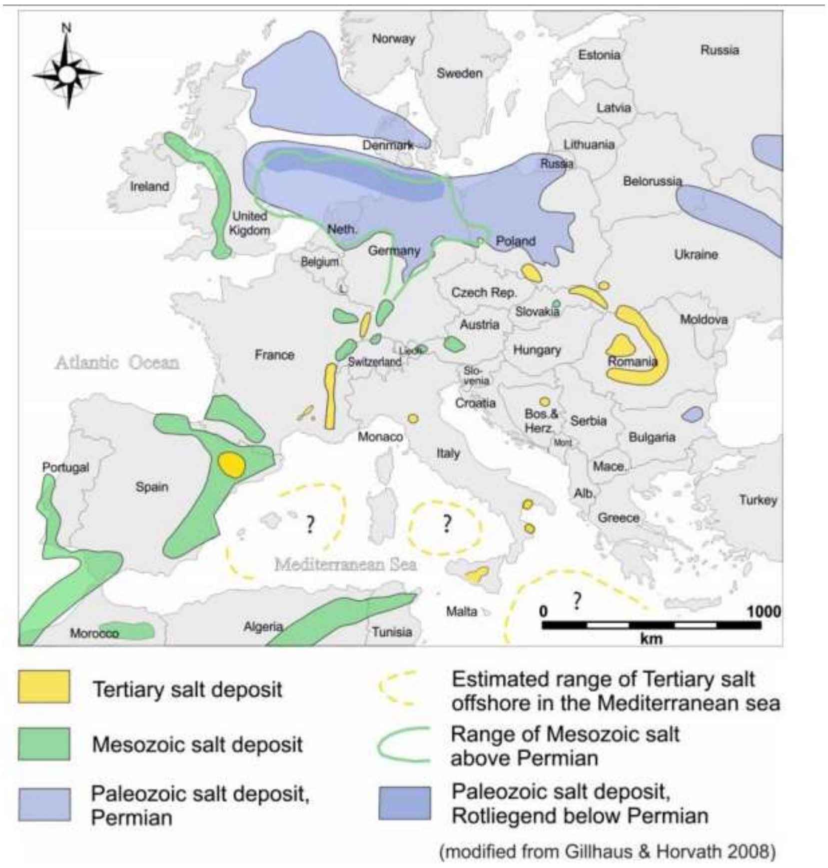
The primary scope of this study is the upstream production of green hydrogen from offshore wind, rather than its downstream storage and use. However, storage of hydrogen will clearly be an important component of the integrated green hydrogen system, especially to compensate for intermittency of production, and it is pertinent to briefly consider Scotland’s potential ability to store hydrogen in geologic formations.

In 2013 the EU-funded HyUnder project assessed geological storage of hydrogen in:

- Salt caverns
- Depleted oil and gas fields
- Aquifers
- Conventionally mined rock caverns

Salt caverns are the only currently proven form of geological hydrogen storage, with several sites operational in the US and UK (Teesside). Salt caverns are also used for short-term storage of natural gas.

Unfortunately, and as shown in Figure 3.23, Scotland lacks any onshore salt deposits. However, there is extensive Permian deposit offshore in the areas covered by existing oil and gas platform and pipeline infrastructure, and by future planned offshore wind developments. Thus, opportunities may exist to provide offshore hydrogen storage in salt caverns.



(modified from Gillhaus & Horvath 2008)

Figure 3.23: Salt deposits in Europe (image : HyStor)

Clearly, Scotland also has huge potential for hydrogen storage in depleted hydrocarbon reservoirs. These reservoirs are well understood from decades of operation and are accessed by existing well, platform and pipeline infrastructure. However, there are a number of fundamental challenges associated with using depleted reservoirs for hydrogen storage, including:

- Hydrogen has a higher diffusivity in pure water than methane. Also, it has a lower viscosity and a lower density than methane. Because the chemical and physical properties of hydrogen are different to those of methane (CH_4), the main component of natural gas, the effects of hydrogen on the reservoir rock and cap rock need careful consideration.
- Due to these differences, there are potential risks involved such as; (i) the conversion of hydrogen to CH_4 and H_2S due to microbial activity, (ii) chemical reaction of hydrogen with the minerals of the reservoir rock/cap rock and thus potential resulting porosity changes, and (iii) the loss of aqueous H_2 by diffusion through the cap rock.
- Presence of residual hydrocarbons which will mix with stored hydrogen and, depending on end use, may then require separation from extracted hydrogen.

Current research recommends choosing depleted gas fields for hydrogen storage where the residual gas has low CO_2 concentrations. The mineralogical composition of the reservoir rocks should contain low amounts of sulphate and carbonate bearing minerals. Research has also focused on developing modelling applications to incorporate the chemical and mechanical effects between the rock material and the working fluids.

The HyStorPor research project, led by the University of Edinburgh, is currently at the forefront of research in these areas (University of Edinburgh, 2020).

3.3.5 Summary

Scotland has a range of existing infrastructure from the oil and gas industry that could be repurposed to develop a hydrogen economy. This includes:

- An extensive infrastructure of existing O&G pipelines, much of which overlays the 2020 Offshore Wind Plan Option areas in the Sectoral Marine Plan and includes four pipelines that currently connect the UK to continently Europe. Examples of repurposing exist but key challenges include long term integrity of now-aging pipelines, especially for the additional challenges of transporting hydrogen, and a potentially extended period between cessation of hydrocarbon production and repurposing for hydrogen transport.
- Several Scottish ports and terminals are well-equipped for hydrogen export and are already actively considering repurposing for hydrogen export. Each port has some compelling advantages:
    - Sullom Voe and Flotta have existing terminal and export infrastructure and are likely to have a vital role in developing the sizeable northerly Scottish offshore wind resource that might otherwise be stranded from mainland connection.
    - Port of Cromarty Firth is well placed for the largest number of ScotWind DPOs and has existing terminal infrastructure and a well-established supply chain. Opportunity Cromarty Firth is well developed and supported.
    - St. Fergus presents an opportunity to build on the ‘first mover’ advantage presented by the Acorn project, though is likely to primarily present a domestic, rather than export, opportunity due to the limitations of Peterhead port. St. Fergus may also provide the most sensible starting point for any hydrogen export pipeline given its nodal location within the current gas pipeline infrastructure.
    - With its existing petrochemical manufacture, Grangemouth is likely best positioned to generate ammonia or LOHC for export.

- Depleted fields and other subsurface structures that would allow for large scale storage of hydrogen. Research in this area however is still in its infancy.

Several individual regional initiatives are already underway, including in Shetland and Cromarty Firth. However, there appears to currently be no overall national strategy or plan and therefore a risk that these initiatives compete rather than collaborate. There may, for example, be merit in multiple sites generating hydrogen but combining export (especially if ammonia or LOHC).

A co-ordinated strategy and plan for hydrogen transportation both within the UK and to Europe is required in order to maximise the efficient re-use of this existing infrastructure and to ensure optimum redevelopment of terminals and ports.

3.4 Supply Chain Database

3.4.1 Approach

3.4.1.1 Overview

A Scottish green hydrogen supply chain database was developed to capture the national supply chain capability and identify Scottish-based companies that are already operating, or planning to operate, within the green hydrogen sector.

The creation of this database followed a similar procedure to that which Xodus employed during the creation of the Scottish offshore wind supply chain database (Scottish Industry Directories, 2020). The process included engagement with hydrogen sector stakeholders to identify Scotland-based companies with relevant interest and capability to support the development, construction and operation of a green hydrogen project using electricity from a wind farm. The hydrogen sector stakeholders contacted as part of this approach were:

- Aberdeen City Council
- Aberdeen Renewable Energy Group
- Argyll and the Islands Council
- Bright Green Hydrogen
- British Compressed Gasses Association
- Decom North Sea
- Deepwind Cluster
- Doosan Babcock
- European Marine Energy Centre
- Energy Technology Partnership
- Forth & Tay Offshore Cluster
- Grangemouth Refinery
- Highland Council
- Highlands and Islands Enterprise
- North East CCUS (NECCUS)
- Oil and Gas Authority
- Oil and Gas Technology Centre
- Oil and Gas UK
- Opportunity North East (ONE)
- Offshore Renewable Energy Catapult
- Opportunity for Renewables Integration with Offshore Networks (ORION) Project
- Orkney Islands Council
- Port of Cromarty Firth
- RenewableUK
- Scottish Enterprise
- Scottish Renewables
- Scottish Gas Networks (SGN)
- Shetland Islands Council
- Scottish Hydrogen & Fuel Cell Association (SHFCA)
- St Fergus Gas Terminal
- Stornoway Port Authority
- Subsea UK
- Western Isles Council

Engagement with stakeholders resulted in the generation of a long list of over 1000 companies from both specific stakeholder suggestions and compilation of stakeholder membership lists. Identified companies were then contacted via direct email and/or through supply chain membership organisations and invited to complete an online survey of their supply capability. The online survey portal was open for 4 weeks to allow interested companies sufficient time to participate. The survey asked suppliers to provide information relevant to this study, including data that could be shared publicly as part of a potential future online Scottish hydrogen industry directory. The information requested as part of the survey included:

- Company Name
- Registration number
- Address
- Website
- Local Authority
- Capability description
- Experience in the hydrogen sector
- Experience supplying parallel sectors
- Categories in which they have current supply capability, or future supply interest

The approach resulted in 118 survey submissions from organisations with an interest in supplying the Scottish hydrogen sector. Analysis of the database of responses was undertaken to generate a view of Scotland's supply chain capabilities. The database was also used to identify the key links between the green hydrogen sector and other relevant parallel industries to assess the wider potential supply chain capability not captured through a database approach.

3.4.1.2 Supply Chain Taxonomy

The key to creating a supply chain database that can be inclusive of potential future suppliers to the sector was to adopt a taxonomy that appropriately covers the breadth and depth of the industry. This allowed for the requirements in each supply chain area to be well defined as well as for overlapping capabilities with supply chains serving parallel sectors to be considered.

A taxonomy was developed that focused on the upstream (generation) to midstream (transport) of the hydrogen supply chain. This classification system was designed to clearly define the various stages of the hydrogen supply chain in broad enough terms that companies – particularly those that have the capacity to participate but have not historically done so - could identify where they could be of service. It was also designed to identify and classify the multitude of products and services required for the development, construction, and operation of a green hydrogen project using electricity from a wind farm.

Five 'Primary' stages of the hydrogen supply chain were identified, with an additional sixth category for 'Sector Support Services' created to capture those companies whose services would not be supplied directly to a hydrogen project but would still support the growth and development of the wider hydrogen sector. These were then broken down into 36 Secondary categories, the specifics of which were further categorised into 142 Tertiary categories. These are given in Table 3.5.

Table 3.5 Hydrogen Supply Chain Taxonomy

Primary category	Secondary category	Tertiary category
Development of Hydrogen Infrastructure	Concept Engineering and Consultancy	Feasibility and pre-concept design studies
		Onshore environmental studies and surveys
		Offshore environmental studies and surveys
	Engineering, Procurement, and Construction (EPC)	Fixed Offshore Structures
		Floating Offshore Structures
		Pipelines
		Process plant design
		Onshore Facilities - Civils and buildings
	Specialist hydrogen shipping design	Specialist hydrogen and/or similar shipping design
	Marinisation design services	Marinisation design services
	Detailed Component Design	Electrolyser design
		Post-processing equipment design
		Storage equipment design
		Pipeline design - onshore
		Pipeline design - offshore
		Electrical system design and modelling
		Control and safety system design
		Metering design
Manufacture of Hydrogen Infrastructure	Marinisation of equipment	Marinisation of equipment
	Electrolysers	Supply of fully assembled electrolysers
		Flow plates - cathode and anode
		Membrane electrode assembly
		Gaskets - anode, mid-cell and cathode
		Housing - anode and cathode
		Valves
		Indicators
		Sensors - pressure and temperature

Primary category	Secondary category	Tertiary category
		Control systems and monitoring
		Outlet manifolds - water and oxygen
		Cooling water systems
		Plate heat exchangers
		ATEX extraction fans
		Water treatment system (demineralisation)
		Hydrogen purification system
	Desalination plants	Supply of fully assembled desalination plants
		Reverse osmosis membranes
		Pressure vessels
		Brine seals
		Valves
		Filters
		Housing
	Compressors	Supply of fully assembled compressors
		Main body steelwork
		Valves
		Gearbox, pistons, driveshafts, other internal steelwork
		Gauges, sensors & indicators
		Motors
		Electronics & control panel
		Gaskets & fastenings
		Buffer tanks & connecting piping
		Steel frame
	Liquefiers & post-processing	Cooling systems
		Filters
		Reactors
		Heat exchangers
		Condensers
		Evaporators
		Separators
		Circulators
		Expanders / Companders
		Blowers

Primary category	Secondary category	Tertiary category
		Adsorbers
		Subcomponents for post-processing machinery
	Tube trailers and storage tanks	Vessels
		Valves
		Filling and extraction components
		Level probes
		Suspensions
		Heat exchangers and heaters
	Offshore Structures	Jackets
		Topsides
		Risers
		Piles
	Pipelines	Pipeline
		Coating
		Anodes
		Flanges bolts and gaskets
		Valves
		Sensors - flowmeters, pressure, temperature
	Electrical system	Heating, Ventilation and Air Conditioning systems
		Switchgear
		Subsea cables
		Sensors and metering
		Control and monitoring systems
		Communication systems
	Health & safety and communications networks	Fire & Gas, ESD and Control Systems
		IT Networks, Offshore comms
	Bespoke manufacturing services	Precision machining
		3D printing
Installation and commissioning of hydrogen infrastructure	Hydrogen production plant installation	Hydrogen production plant installation
		Commissioning
	Offshore Structures installation	Jackets
		Topsides
		Piling

Primary category	Secondary category	Tertiary category
		Anchoring
		Site survey
		Pipeline lay
		Pipeline trenching / backfilling
	Offshore cable installation	Offshore cable installation
	Pipeline installation	Landfall
		Riser
		ROV / diver
		Pipeline-handling equipment
		Pressure testing
		Commissioning
	Ports installation	Installation port infrastructure
		Heavy lifting port services
	Onshore works	Onshore civils
		Onshore logistics
Operation, maintenance and decommissioning of hydrogen infrastructure	Training	Training
	Ports infrastructure to support offshore O&M	O&M port infrastructure
		Hydrogen handling port services
	Onshore logistics	O&M coordination
		Transport of hydrogen logistics - road transport
	Offshore logistics	Transport of hydrogen logistics - export overseas by subsea pipelines
		Transport of hydrogen logistics - export overseas by shipping
		Crew Transfer vessels
	Health and safety	Health and safety inspections
		Health and safety equipment
	Hydrogen plant maintenance and service	Electrolyser inspection, repair, refurbishment and replacement
		Inspection and repair of post-production processing plants
		Inspection and repair of storage and delivery components
	Balance of plant maintenance and service	Desalination plant inspection and repair

Primary category	Secondary category	Tertiary category
		Offshore substructure inspection and repair
		Pipeline inspection and repair
		Electrical equipment inspection and repair
		Valve inspection, repair and maintenance
		Tooling and consumables
	Operations and maintenance support and IT support	Software and IT support
	Offshore decommissioning services	Offshore decommissioning services
	Onshore decommissioning services	Onshore decommissioning services
Transport of Hydrogen	Road transport delivery	Trucks
		Rail
	Shipping delivery	Tankers
		Other seagoing vessels to carry hydrogen
Sector Support Functions	Professional services	Consultancy
		Trade associations and bodies
		Health & safety
	R&D and education	Non-academic research & technology organisations
		Universities (including institutes)
		Further education college
		Other public and private organisations

3.4.2 Survey Results

3.4.2.1 Overview of Survey Respondents

The hydrogen supply chain survey received 118 responses, both from companies currently operating in Scotland and those with future ambitions to operate in Scotland.

Prior to processing and analysis, the raw data was cleaned to remove duplicates and responses from companies whose current and future supply is not suitable for the hydrogen supply chain. This resulted in a total of 109 unique responses from companies suitable for consideration in this study. These responses were further assessed for whether a company’s stated supply chain capability or ambition was consistent with the company’s own description of their current operations, with inconsistent responses removed. For instance, if a company stated they manufactured jacket structures while their capability statement and company profile showed they were primarily involved in the structural design process, then their response was edited to reflect this.

As well as being asked to indicate which areas of the supply chain they can, or aim to, participate in companies were asked to indicate in which Scottish Local Authority areas they are based. The number of companies active in each local authority area is indicated in Figure 3.24. As only one address could be supplied per company, it is possible that each company also operates or provides some services from an alternative location from their given address. Where companies supply multiple areas, further work is required to determine exactly which products or services are provided from which location.

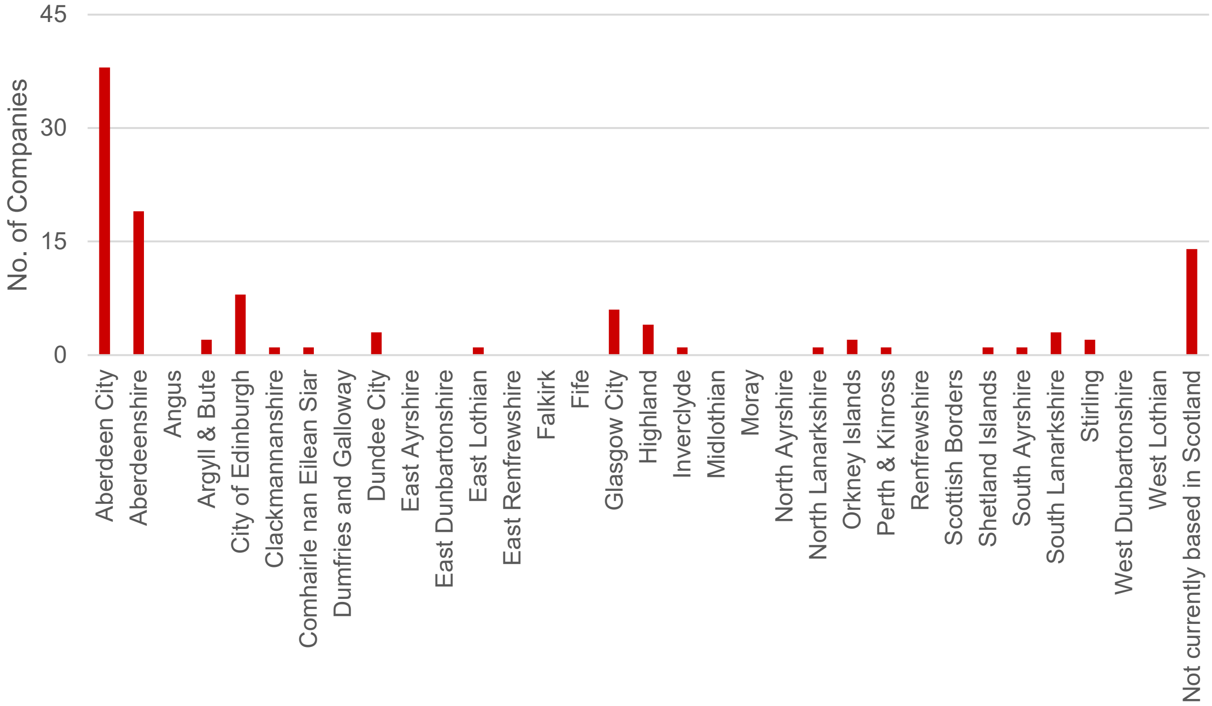


Figure 3.24 Local Authority Area of Survey Respondents

As can be seen in Figure 3.24, the majority of respondents (52%) are from North-East Scotland, particularly Aberdeen City and Aberdeenshire. Other clusters can be found in major population centres, such as Edinburgh (7% of respondents), Glasgow (6% of respondents), and Dundee (3% of respondents).

Approximately 13% of respondents are not currently based in Scotland. Of the 14 non-Scottish companies that responded, five were based in the rest of the UK (four in England and one in Northern Ireland), four were based in Norway, two in the USA, and one each in France, Germany, and Spain.

Respondents were also asked to rank their current involvement in the hydrogen supply chain, from ‘No Involvement’ to ‘Somewhat Involved’ and ‘Highly Involved’. As this is a subjective selection made based on each company’s perception of the market and their standing in it, these participation rankings were largely left unedited. The few exceptions to this were when a company’s stated capability and/or ambition did not align with their stated level of involvement. A breakdown of company level of involvement in the hydrogen supply chain by Scottish Local Authority area is shown in Figure 3.25 (noting that Local Authority areas with no responses have been omitted from the figure for clarity).

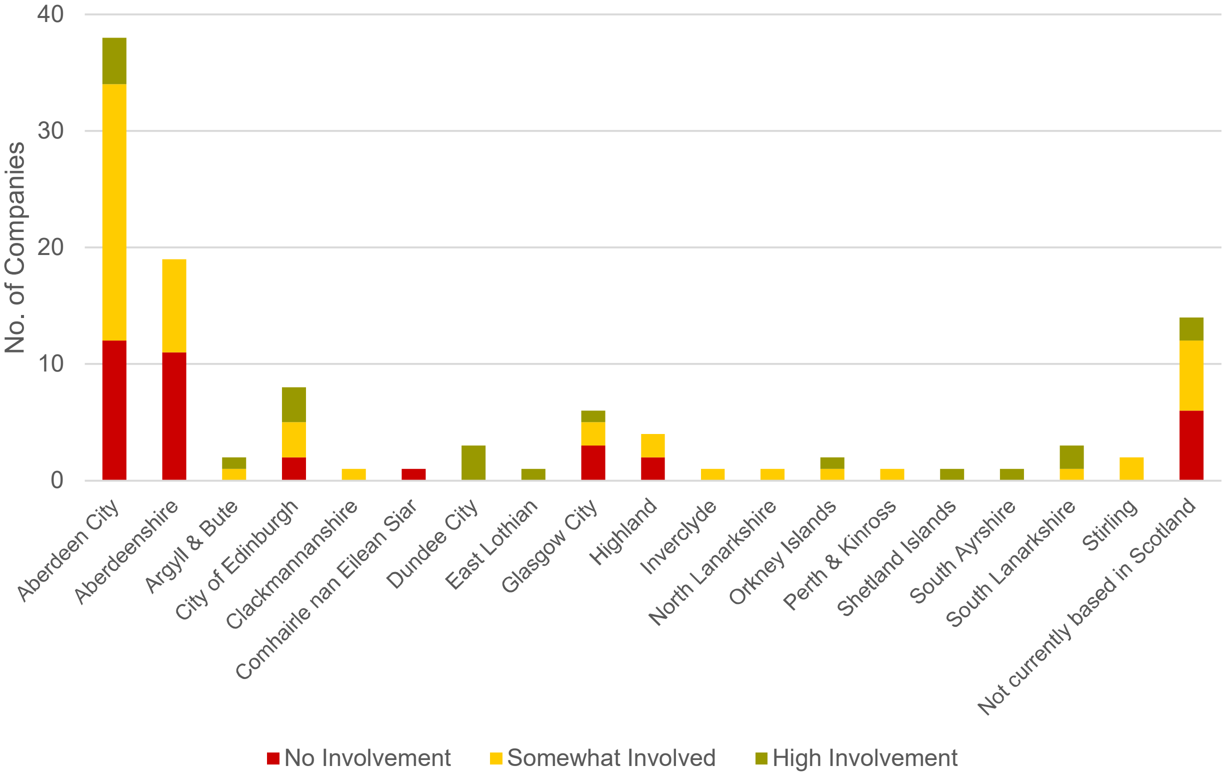


Figure 3.25 Companies' self-assessed level of current involvement in the Scottish hydrogen sector supply chain by Local Authority area

Most companies perceived themselves to be 'Somewhat Involved' or 'Highly Involved' with the Scottish hydrogen sector. Companies that responded to the survey but are not actively involved in the hydrogen sector were most likely to be based in the major cities: Aberdeen, Edinburgh, and Glasgow. Companies outside these areas (Aberdeenshire being the exception) tended only to respond if they were already somewhat or highly involved in the hydrogen sector.

As companies were asked to self-assess their level of involvement in the hydrogen supply chain, the response is highly subjective and seems to vary quite considerably. Some companies that offer only one product/service deem themselves to be highly involved, whereas others who offer many deem themselves to only be somewhat involved or not involved at all. While there is not a strict pattern, it seems that companies have broadly determined their level of involvement according to how tailored their product is for the hydrogen sector. For instance, a higher proportion of companies offering supply of fully assembled electrolysers see themselves as being highly involved in the hydrogen sector than companies whose services apply to numerous sectors (e.g. offshore decommissioning), which has a higher proportion of companies expressing lower levels of involvement. The more specialised to hydrogen a company's service offering is, the more likely they are to perceive themselves to be highly involved in the sector.

Companies were also asked to indicate in which other sectors they are active and have expertise. This is shown in Figure 3.26. The sectors chosen to align with the Scottish Industry Directories, plus the addition of Oil and Gas which has no specific Scottish Industry Directory but has clear synergies with the hydrogen sector. Note that companies were able to select as many options as they deemed relevant and have been counted within each service offering.

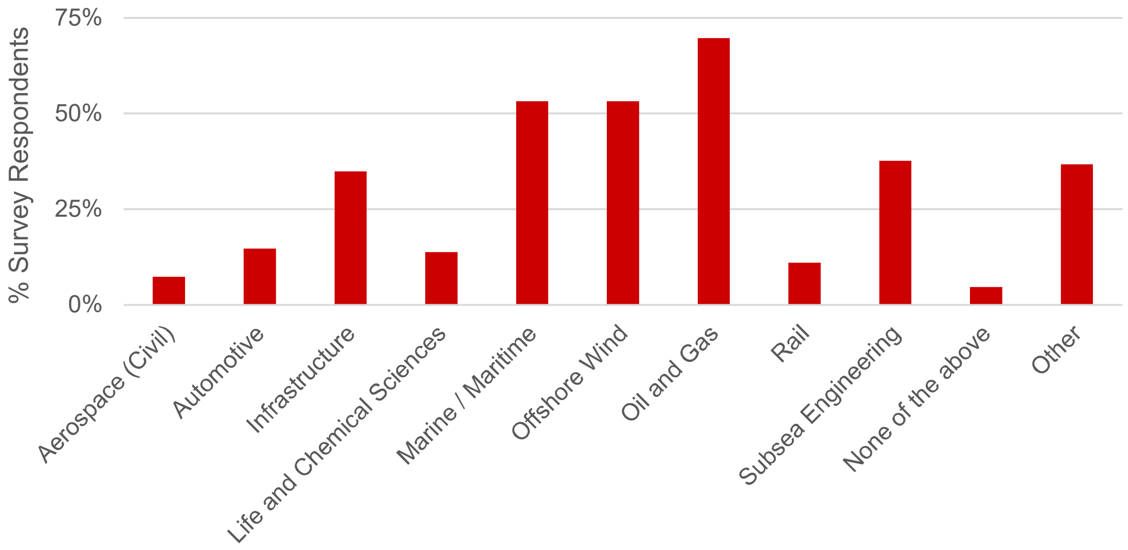


Figure 3.26 Parallel Sector Areas of Expertise of Survey Respondents

The main sector in which respondents have existing experience is Oil and Gas, followed by Marine / Maritime, Offshore Wind, and Subsea Engineering. Most companies were active across multiple experience areas, further suggesting that the knowledge and skills required in these sectors are broadly aligned and transferable and that we might expect significant overlap between their supply chains.

Many of the companies that selected the ‘Other’ option have expertise in forms of renewable energy other than offshore wind, including onshore wind and solar. Very few companies selected ‘None of the above’, but most of those that did outlined their activities in the ‘Other’ category and are active in areas of renewable energy outwith offshore wind.

The distribution of experience shown in Figure 3.26 aligns with the data shown in Figure 3.25; Aberdeenshire and Aberdeen are well established hubs for the oil and gas, offshore wind, marine / maritime, and subsea engineering sectors. The fact that many of these companies have assessed themselves to be involved to some degree in the hydrogen sector suggests that there is significant overlap between the supply chains of these industries and hydrogen. As a result, many such companies could be expected to have transferable skills and expertise that could be leveraged to meet the needs of the hydrogen sector.

3.4.2.2 Primary Level Overview of Hydrogen Supply Chain

As indicated in the taxonomy shown in Table 3.5, companies were asked to indicate which products and services (specified in the Tertiary categories) they could provide within six Primary stages of the hydrogen supply chain. The breakdown of the percentage of respondents offering services in each of the six Primary stages is shown in Figure 3.27. No distinction has been made between whether a company either has current supply capability or has an ambition for future supply in this area. Figure 3.27 shows the percentage of companies active in each Primary stage of the supply chain and not the extent to which they are active within this i.e. if a company has indicated activity in each of the secondary or tertiary categories of any of the primary stages then they are counted equally to a company that has selected only one such category in that stage.

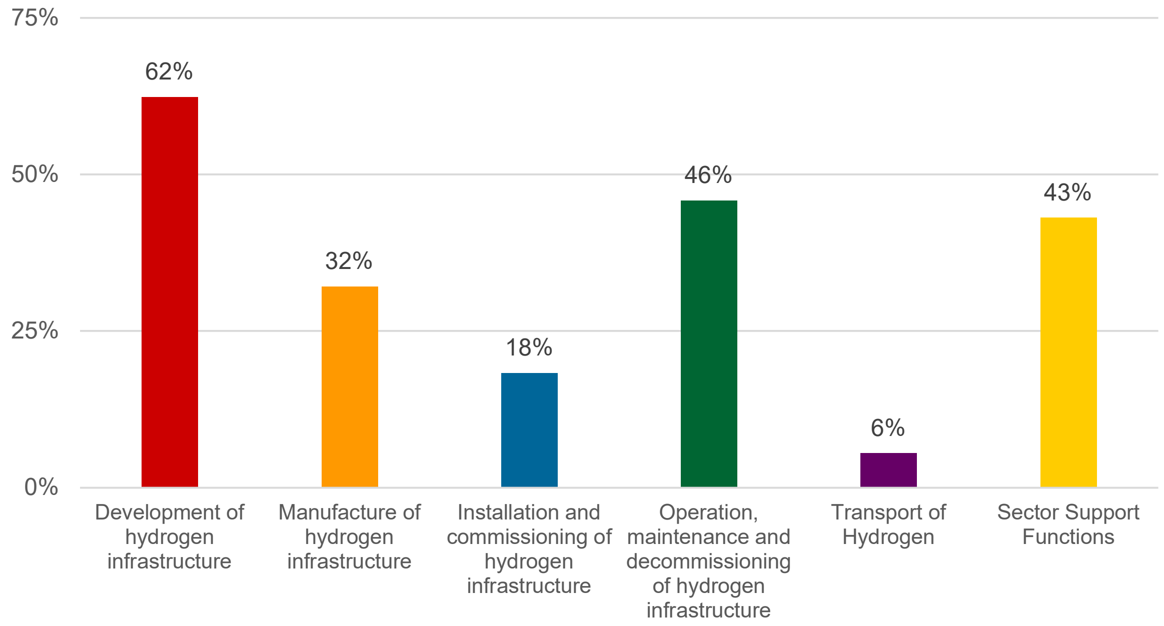


Figure 3.27 - Percentage of survey respondents active in each primary stage of the hydrogen supply chain

The majority of respondents offer services in the development of hydrogen infrastructure i.e. in design and concept engineering services. Slightly under half of respondents offer services in O&M and decommissioning of hydrogen, and slightly fewer offer sector support functions. As many of these services are desk-based roles, this correlates with the data shown in Figure 3.24 where most respondents were based in Scotland's major cities. Approximately one third of respondents offer Manufacturing services. The number of companies offering Installation services is lower, and Transport services lower still. This is to be expected given that the hydrogen sector is still in the early stages of development and so there have not been many projects for companies to participate in providing manufacturing and installation services. Very few companies offer transport of hydrogen services.

Most companies were active or expressed interest in numerous stages of the supply chain. Very few companies were only active in a single supply chain stage:

- 8 companies were only active in development
- 5 companies were only active in manufacturing
- 0 companies were only active in installation and commissioning
- 4 companies were only active in operations, maintenance, and decommissioning
- 0 companies were only active in transport
- 15 companies were only active in sector support functions (most of whom offered consultancy services but not design)

Companies offering services in the development stage (mostly related to design) were most likely to also offer services in another stage of the supply chain, particularly operations and sector support services (predominantly consultancy).

Figure 3.28 shows how the number of companies active across each Primary stage of the hydrogen supply chain varies according to the industries in which they have experience. Note that double counting is to be expected as companies were able to be active in numerous stages of the supply chain as well as across numerous industries.

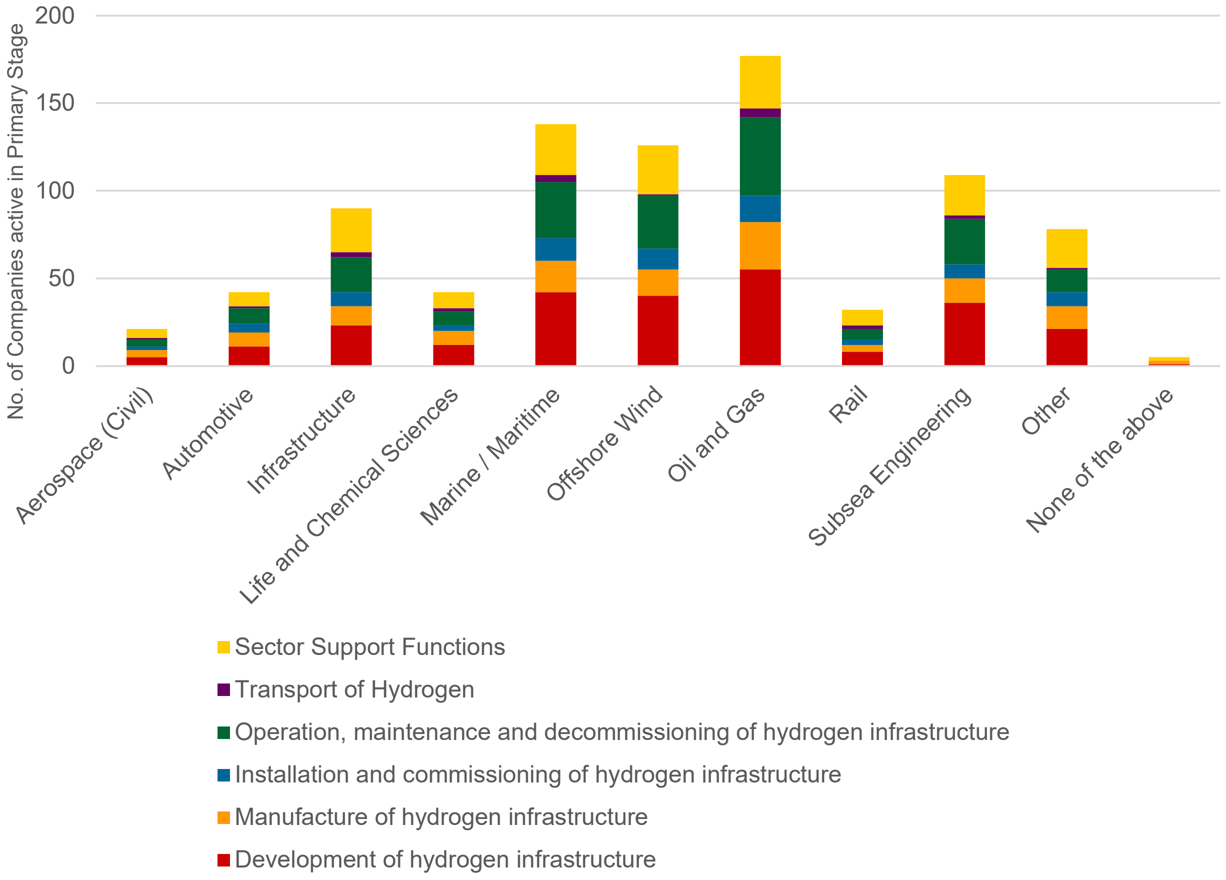


Figure 3.28 - Areas of Hydrogen Supply Chain Services by Areas of Company Experience

Within each experience sector, the proportion of companies active in each Primary stage of the hydrogen supply chain remains fairly consistent; the sectors in which companies have experience does not significantly affect the stages of the hydrogen supply chain in which they participate. This suggests that none of the Primary stages of the hydrogen supply chain are being predominantly served by parallel supply chains in any one of the other experience sectors. Rather, the experience sectors are likely to share many aspects of their supply chains, which would also be suitable for providing products and services to the hydrogen industry.

3.4.2.3 Secondary Level Overview of Hydrogen Supply Chain

The 6 Primary stages of the hydrogen supply chain are broken down into 36 more detailed categories as shown in the Taxonomy in Table 3.5. Note that these are categories of products and services offered by companies and not the products and services themselves. Figure 3.29 shows the number of companies that can or are aiming to offer services in each Secondary category. This provides a clearer idea of the capabilities that each survey respondent either has or aims to have within the hydrogen supply chain, as well as highlighting areas that may currently be underserviced and would provide an opportunity for new entrants to the market.

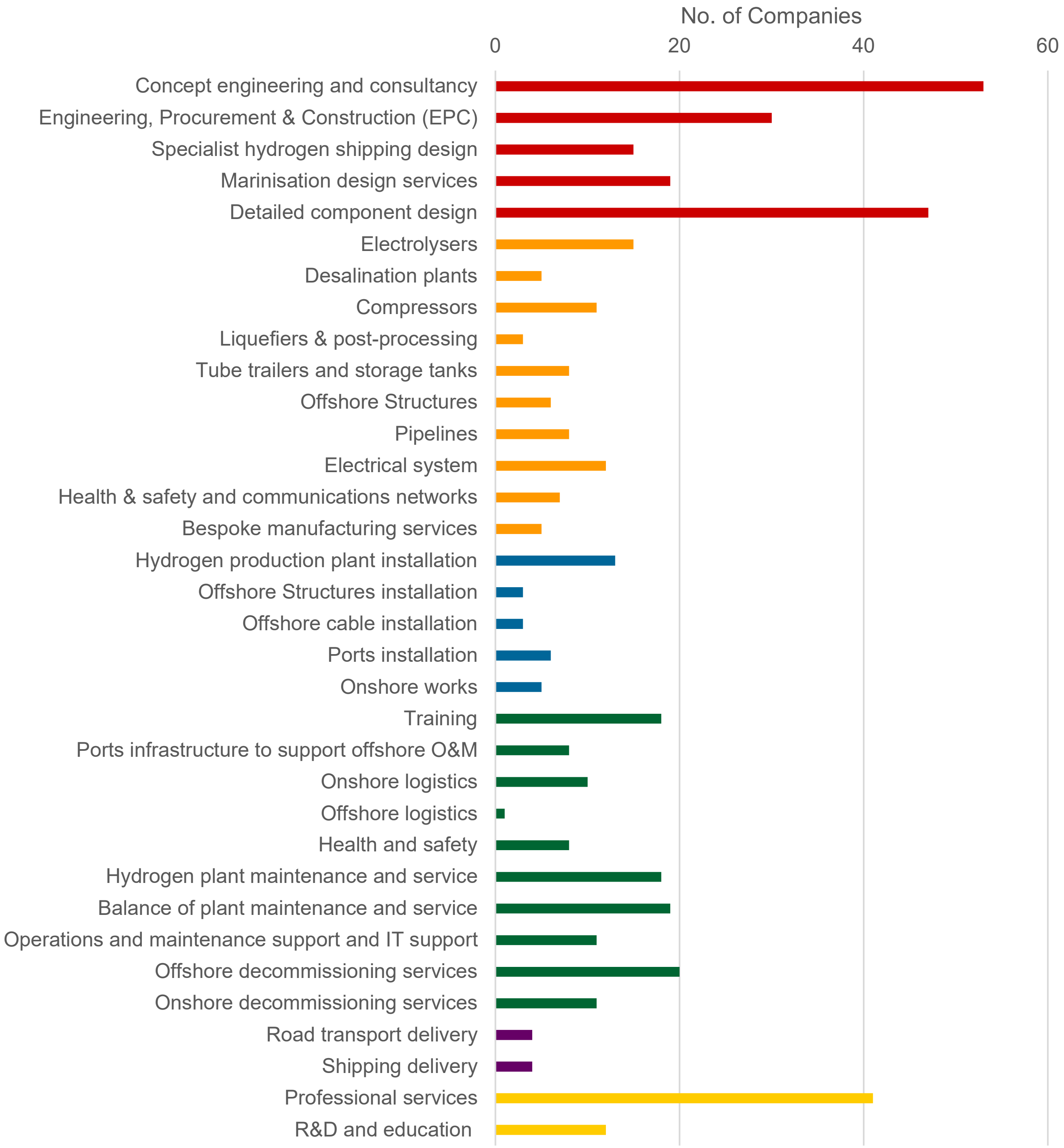


Figure 3.29 - Number of companies offering secondary level services throughout the hydrogen supply chain

Figure 3.29 shows that there are a high number of companies involved in the development of hydrogen infrastructure, particularly in engineering and design. Almost half of the survey respondents have indicated that they have capability or would be interested in providing such services. Significantly fewer companies have indicated such an interest in participating in the Construction stages (Manufacturing and Installation) of the hydrogen supply chain. However, this could be reflective of the nascent state of the Scottish hydrogen sector.

With so few projects currently in development, there is a lack of opportunity for companies to participate in manufacture and installation of hydrogen infrastructure. It is expected that as the sector matures, and more projects are developed, greater interest will be shown in participating and building capability in these stages of the supply chain.

Fewer than one in five survey respondents indicated capability or ambition to provide O&M and Decommissioning services. This is surprisingly low given parallels between this stage and broader Health & Safety supply chains used by similar sectors (e.g. oil and gas, offshore wind, subsea engineering, etc.). This could indicate that the quantity of survey responses was too low to provide a comprehensive overview of Scottish capabilities or could suggest that companies do not currently perceive that their sectors overlap with the needs of the hydrogen supply chain. If the latter, then early engagement with suitable companies to identify areas of overlap and inform them of opportunities to engage would be appropriate.

The supply chain stage with the fewest number of companies participating is Transport. It appears that bespoke transport – as is required for hydrogen – does not currently have a strong supply chain presence. More work is needed to quantify the level and type of transportation required and to engage with relevant companies in other sectors to identify where supply chains might overlap.

Finally, the number of companies providing professional support services and R&D was fairly high (just under 40%). While use of these companies will not directly contribute to augmenting the volume of local Scottish content in any one hydrogen project, they exist to grow Scotland’s knowledge and capability to develop a strong hydrogen sector. This will provide further benefits, such as improving Scotland’s export potential (providing products and services to other nations looking to develop hydrogen projects) and supporting Scotland’s global reputation as a leader in renewable energy.

Figure 3.30 shows the number of companies offering each Secondary level of the hydrogen supply chain according to how they view their involvement in the hydrogen supply chain at large. Areas with higher numbers of companies that see themselves as highly or somewhat involved can indicate strength in this part of the supply chain and, conversely, areas that have few companies offering services or only companies that are not yet involved can indicate where there is weakness. On this basis, the hydrogen supply chain seems to be particularly strong in services relating to concept engineering and consultancy, detailed component design, and professional services. Areas that are weaker include manufacture of offshore structures and H&S and communications networks, as well as various installation services. Engagement with companies offering these services is needed to identify the support they require to commit to providing these services to the hydrogen supply chain.

The fact that there is a mix of involvement in the development, operations, and sector support stages of the hydrogen supply chain indicates that there is widespread awareness of the industry and an opportunity for more companies to become involved with it. In total, 37 companies answered the survey but felt that they had ‘No involvement’ in the current supply chain. These companies predominantly had experience in oil and gas, offshore wind, marine/maritime, or subsea engineering. Given the higher levels of involvement from other companies in these sectors, there is real scope for many of these companies to become more actively involved.

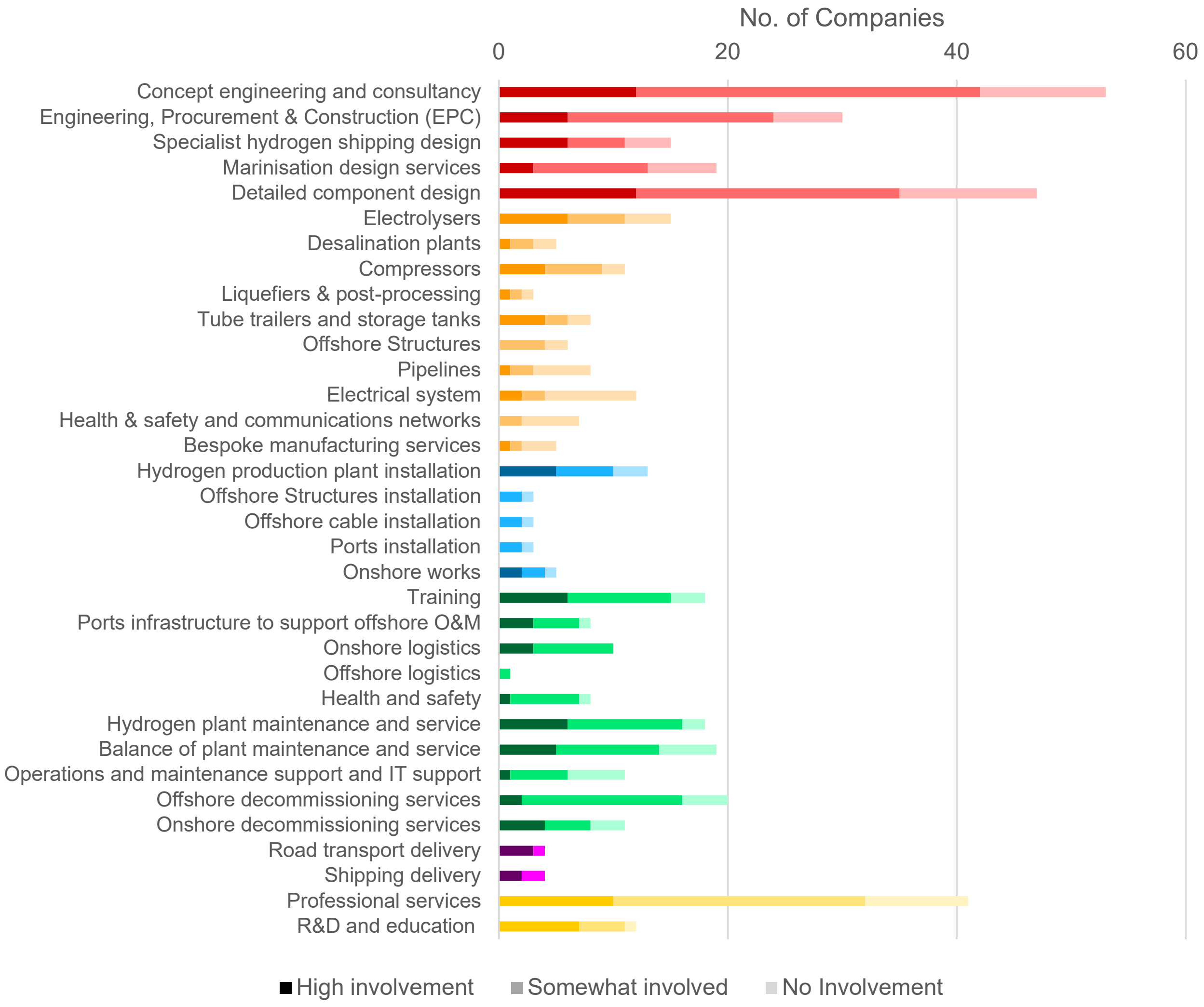


Figure 3.30 - No of companies of companies offering services throughout Scottish hydrogen supply chain broken down by self-assessed level of involvement

3.4.2.4 Tertiary Level Overview of Hydrogen Supply Chain

The tertiary levels of the hydrogen supply chain taxonomy (as shown in Table 3.5) are the products and services that companies may offer. This section analyses the companies that have stated an ability or desire to provide these products/services, considering each of the Primary stages of the supply chain in turn.

3.4.2.4.1 Development of hydrogen infrastructure

Figure 3.31 and Figure 3.32 show the number of companies that stated they would be able or interested in providing each of the products and services that comprise the 'Development of Hydrogen Infrastructure' stage of the hydrogen supply chain. In Figure 3.31, this was further broken down to represent how that company viewed its current level of involvement in the hydrogen supply chain at large, with darker shades representing 'High involvement' and lighter shades representing 'No Involvement'. Figure 3.32 shows the areas in which the company has expressed current involvement. Please note that companies were able to select multiple experience areas and therefore may have been counted multiple times for each service offering.

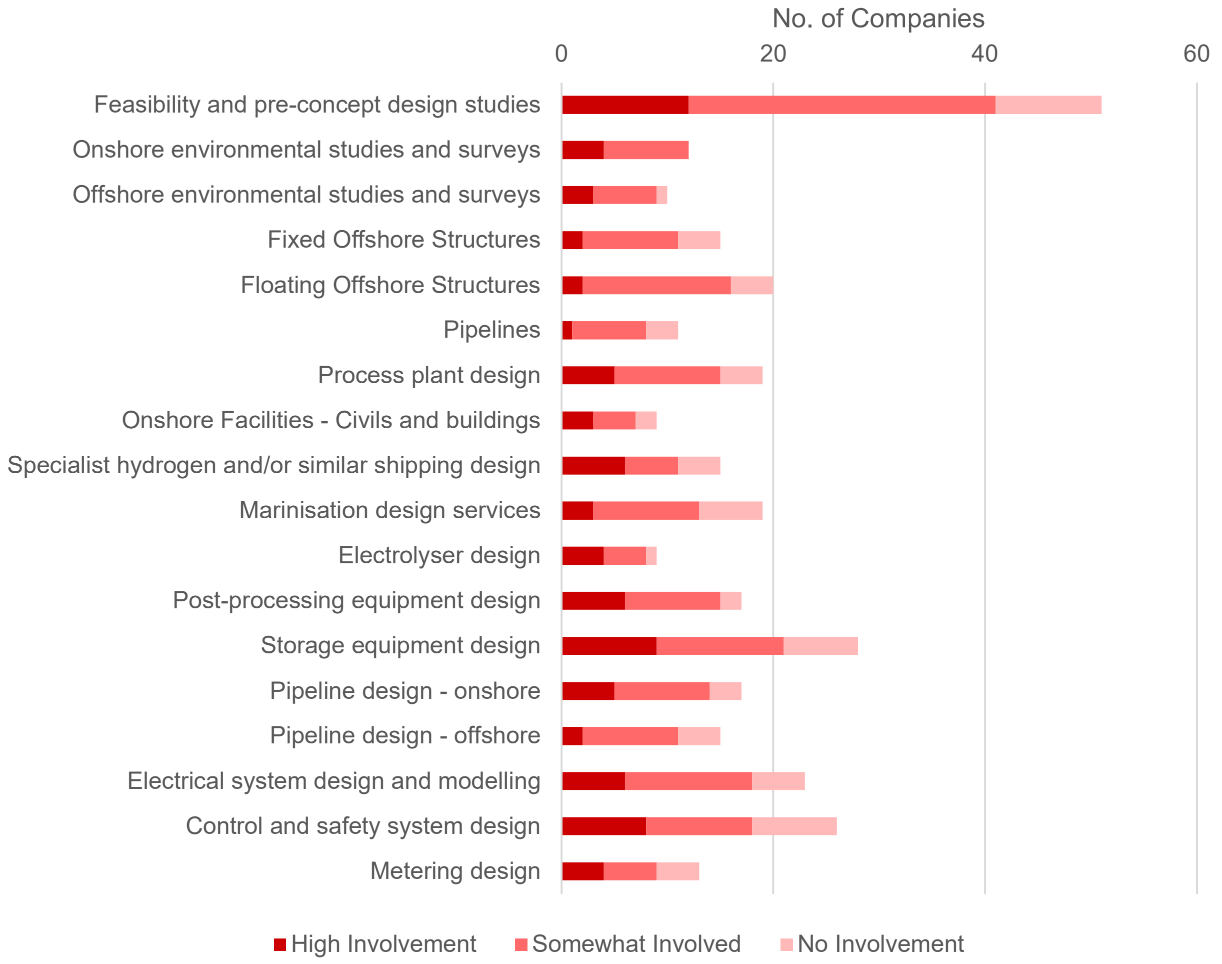


Figure 3.31 - Number of companies offering services in Development of Hydrogen Infrastructure and their self-assessed involvement in the hydrogen sector

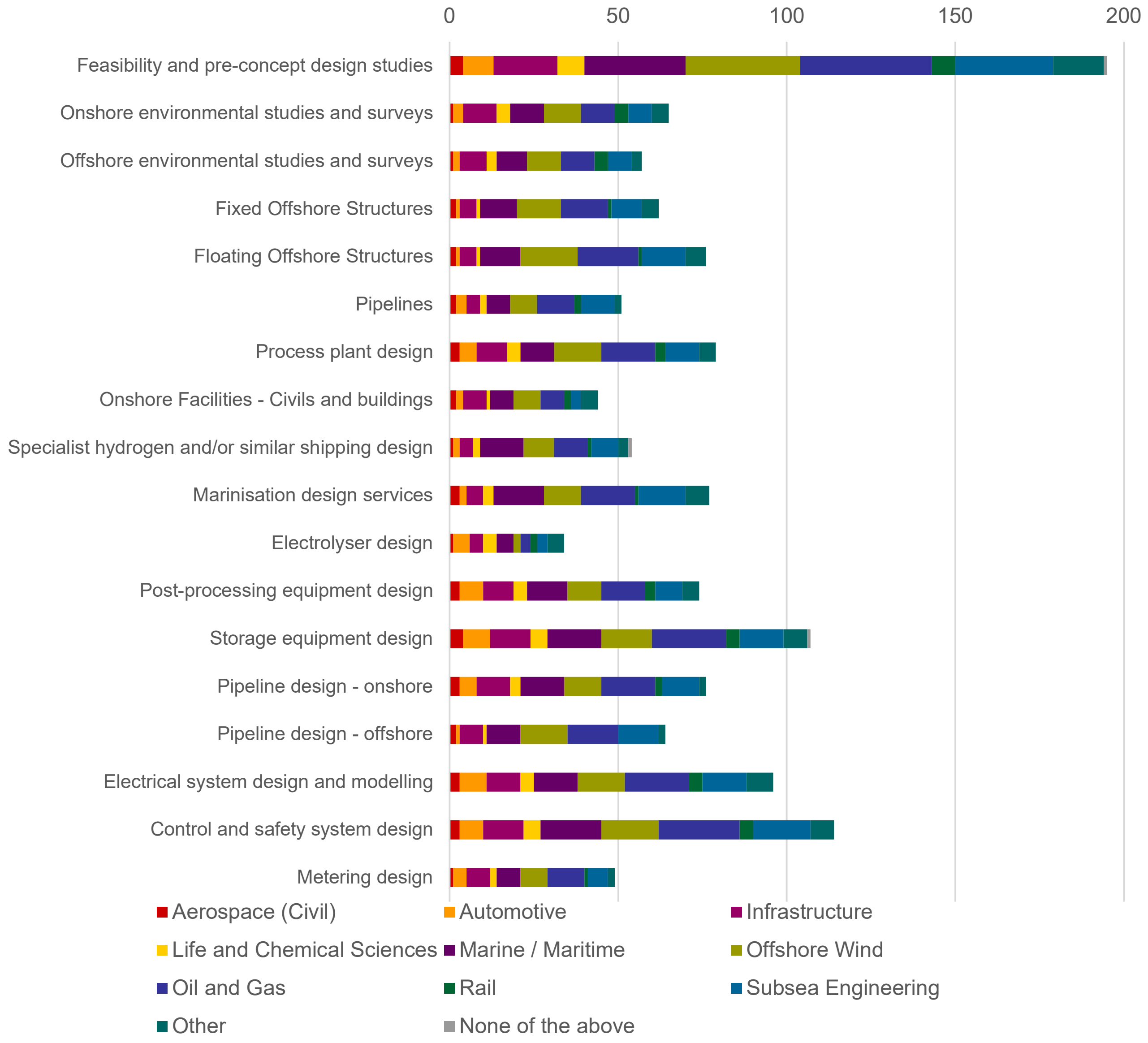


Figure 3.32 Number of companies per area of experience able or aiming to provide products/services to the Development of Hydrogen Infrastructure stage of the hydrogen supply chain

Almost half of survey respondents expressed an interest in providing ‘Feasibility and pre-concept design studies’, the most popular category within Development of Hydrogen Infrastructure. A high proportion of these companies (80% of those who expressed an interest in this area) consider themselves to be either highly or somewhat involved in the hydrogen supply chain. The second and third most popular choices were ‘Storage equipment design’ and ‘Control and safety system design’ respectively, and these also had the second and third highest number of companies considering themselves to be ‘highly involved’ in the hydrogen supply chain. This suggests that design capability is currently a particular strength of the Scottish hydrogen supply chain.

The areas with the least interest (in order from low to high) include ‘Electrolyser design’, ‘Onshore facilities – civils’, and ‘Pipelines’. This could be a result of uncertainty around exact hydrogen requirements resulting from the nascent state of the sector.

Figure 3.32 shows that companies willing to provide design services are predominantly coming from ‘Oil and Gas’, ‘Offshore Wind’, ‘Marine / Maritime’, or ‘Subsea Engineering’ backgrounds (in order of prevalence, from high to low). Indeed, this holds true for each of the tertiary levels within the ‘Development of Hydrogen Infrastructure’ supply chain stage.

3.4.2.4.2 Manufacture of Hydrogen Infrastructure

Far fewer companies expressed an ability or ambition to offer products and services in the Manufacture of Hydrogen Infrastructure than in Development. The category with the greatest interest was ‘Control and Monitoring Systems’ with a total of ten companies and twenty of the tertiary levels received no commitment at all.

Figure 3.33 shows the total number of companies offering each product/service within the Manufacture of Hydrogen Infrastructure stage as well as the perceived involvement of these companies in the hydrogen supply chain at large. There are some sizeable gaps in the supply chain; 20 areas have no companies able or aiming to provide services in them, and 10 areas were selected only by companies that do not perceive themselves to currently be involved with the hydrogen supply chain. Of these latter ten, the most popular were ‘Communication Systems’ and ‘Sensors and metering for electrical systems’. For categories where there is interest from companies that do not perceive themselves to be involved, there is an opportunity for engagement to turn ambition into action.

It is also possible to identify future strengths in the manufacturing supply chain, should companies’ ambitions be realised. For instance, categories that have been predominantly selected by companies that perceive themselves to be highly or somewhat involved in the hydrogen supply chain already. Examples include ‘Supply of fully assembled electrolysers’, Supply of fully assembled compressors’, and ‘Vessels for tube trailers and storage tanks’.

Figure 3.34 shows the number of companies per area of experience able or aiming to provide each product/service in the Manufacture stage of the hydrogen supply chain. It is important to note that for products that appear to be equally well supplied by each experience area this is normally the result of a small number of companies offering this product across many parallel supply chains (and being counted for each one), rather than many companies active in only one supply chain offering this. Companies with oil and gas, offshore wind, marine/maritime, or subsea engineering experience seem to be interested in providing services across Manufacturing, though are uniquely interested in providing offshore structures. Other service areas seem to attract interest from companies across the experience areas, suggesting products and experience in parallel supply chains are readily transferable to hydrogen developments.

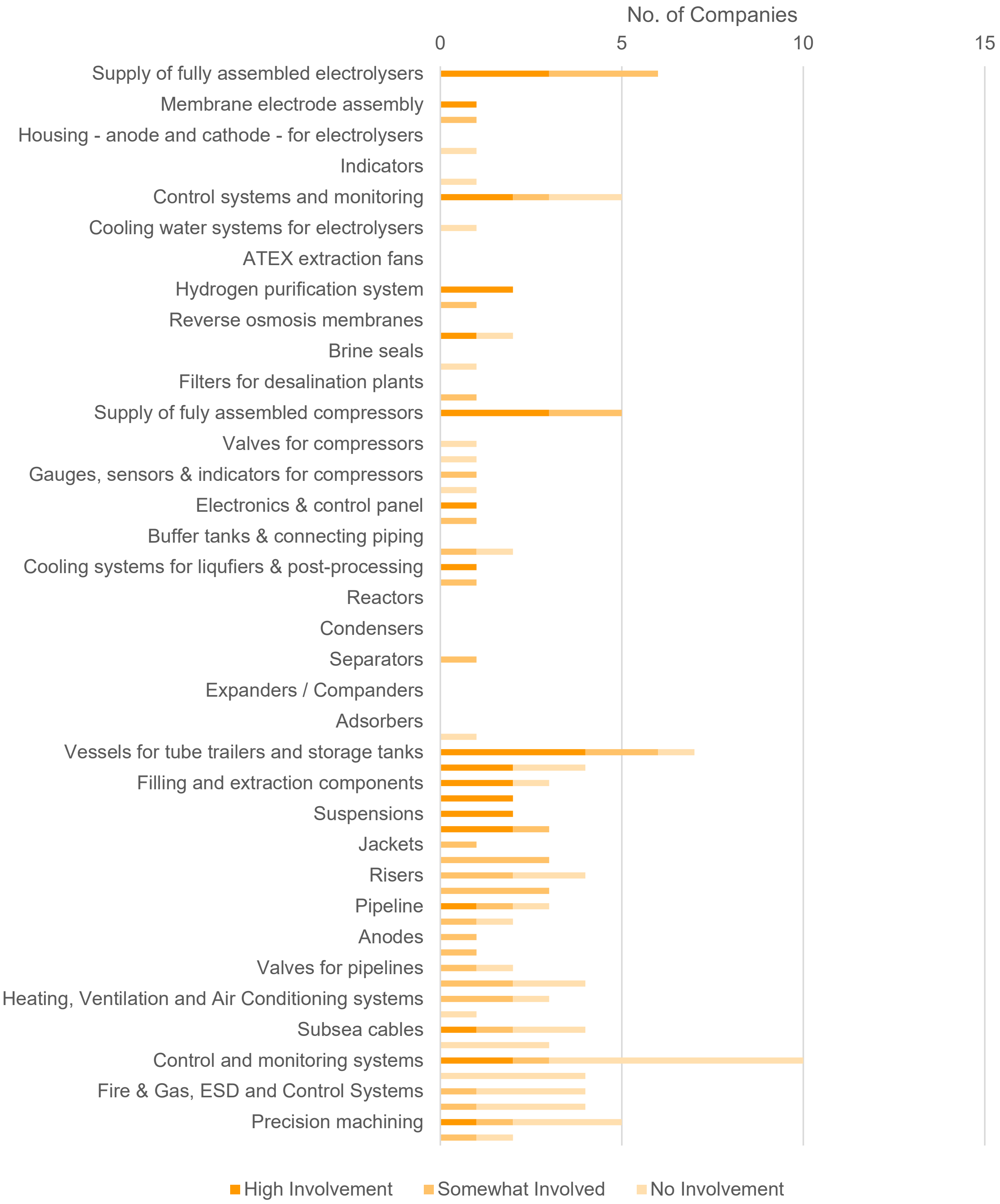


Figure 3.33 - Number of companies offering services in Manufacture of Hydrogen Infrastructure and their self-assessed current involvement in the hydrogen sector

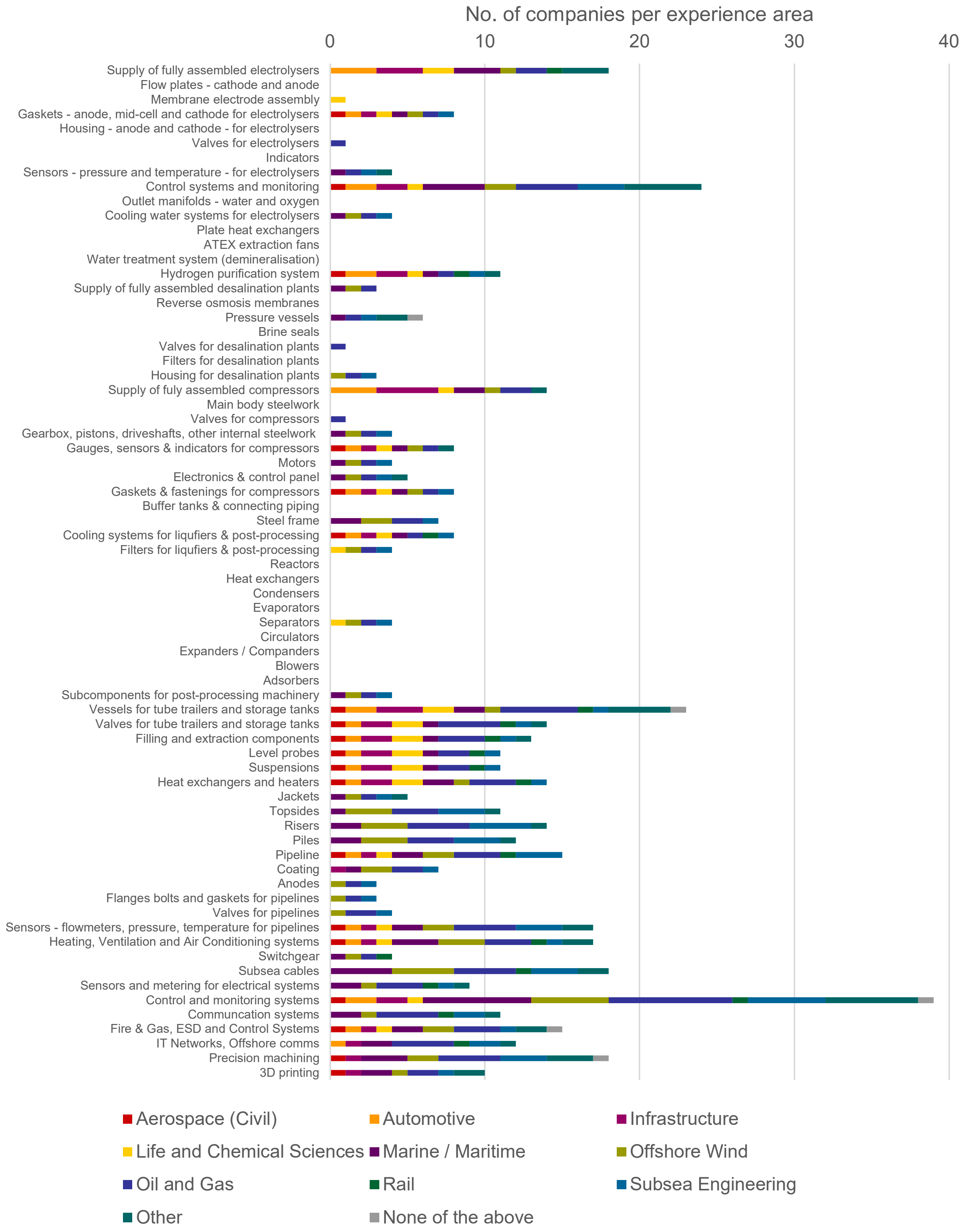


Figure 3.34 Number of companies per area of experience able or aiming to provide products/services to the Manufacture of Hydrogen Infrastructure stage of the hydrogen supply chain

3.4.2.4.3 Installation and Commissioning of Hydrogen Infrastructure

A total of 20 companies stated they had an interest in providing services for the installation and commissioning of hydrogen infrastructure.

Figure 3.35 shows the number of companies willing to offer each of the 14 installation/commissioning services, broken down according to their perceived level of involvement in the overall hydrogen supply chain. The two most selected services are also the two areas preferred by companies that are either highly or somewhat involved in the hydrogen supply chain: hydrogen production plant installation, and commissioning. This suggests these areas are a strength of the Scottish hydrogen supply chain as it stands. The same two companies (both of whom perceive themselves to be ‘somewhat involved’), are interested in providing installation and commissioning services for many of the products/services in the installation stage. Early engagement with these companies could identify their exact capability and capacity to supply Scotland’s hydrogen sector and where they might need further support to grow supply as demand increases.

Figure 3.36 shows the parallel sectors in which these companies also have experience. Many of the companies are active across several parallel sectors, with no one area of experience standing out as being particularly well matched with this stage of the hydrogen supply chain. Companies active in the aerospace, automotive, and life and chemical sciences fields seem only to be interested in providing services that can be conducted onshore. Companies with offshore experience (e.g. in oil and gas, offshore wind, or subsea engineering) however seem comfortable offering services in both offshore and onshore environments.

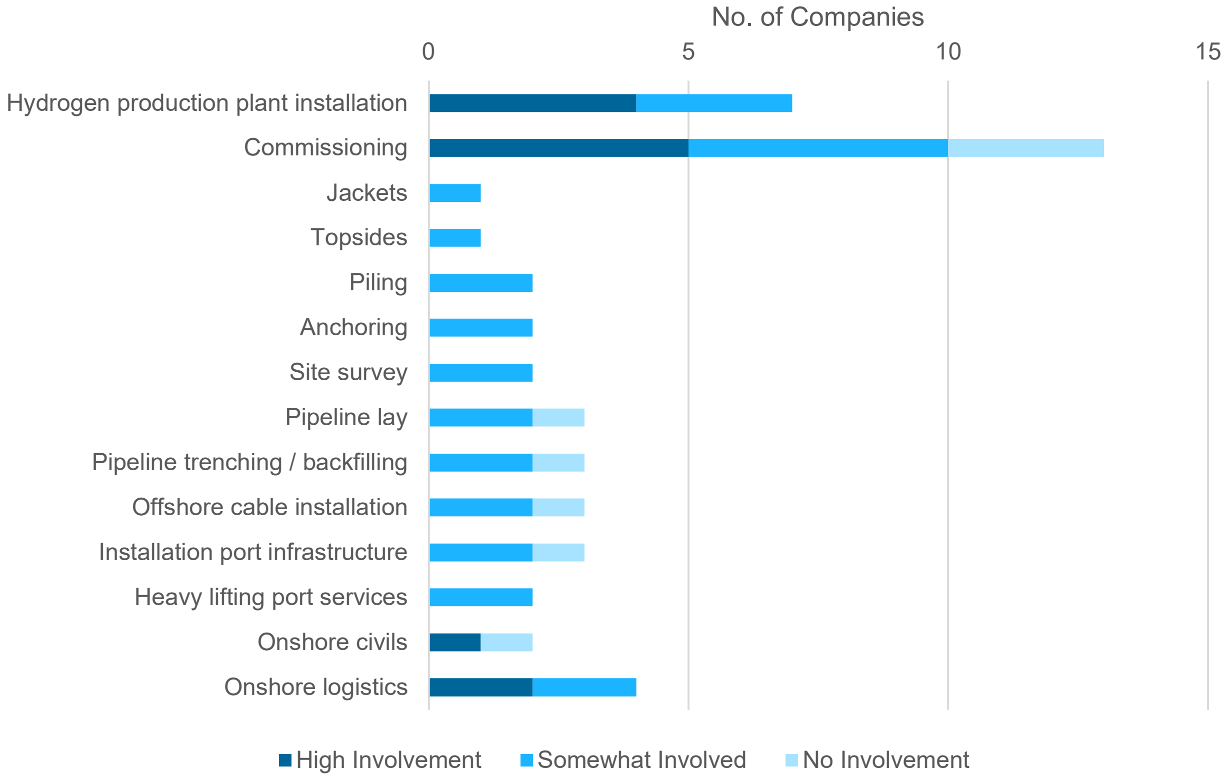


Figure 3.35 - Number of companies offering services in Installation and Commissioning of Hydrogen Infrastructure and their self-assessed current involvement in the hydrogen sector

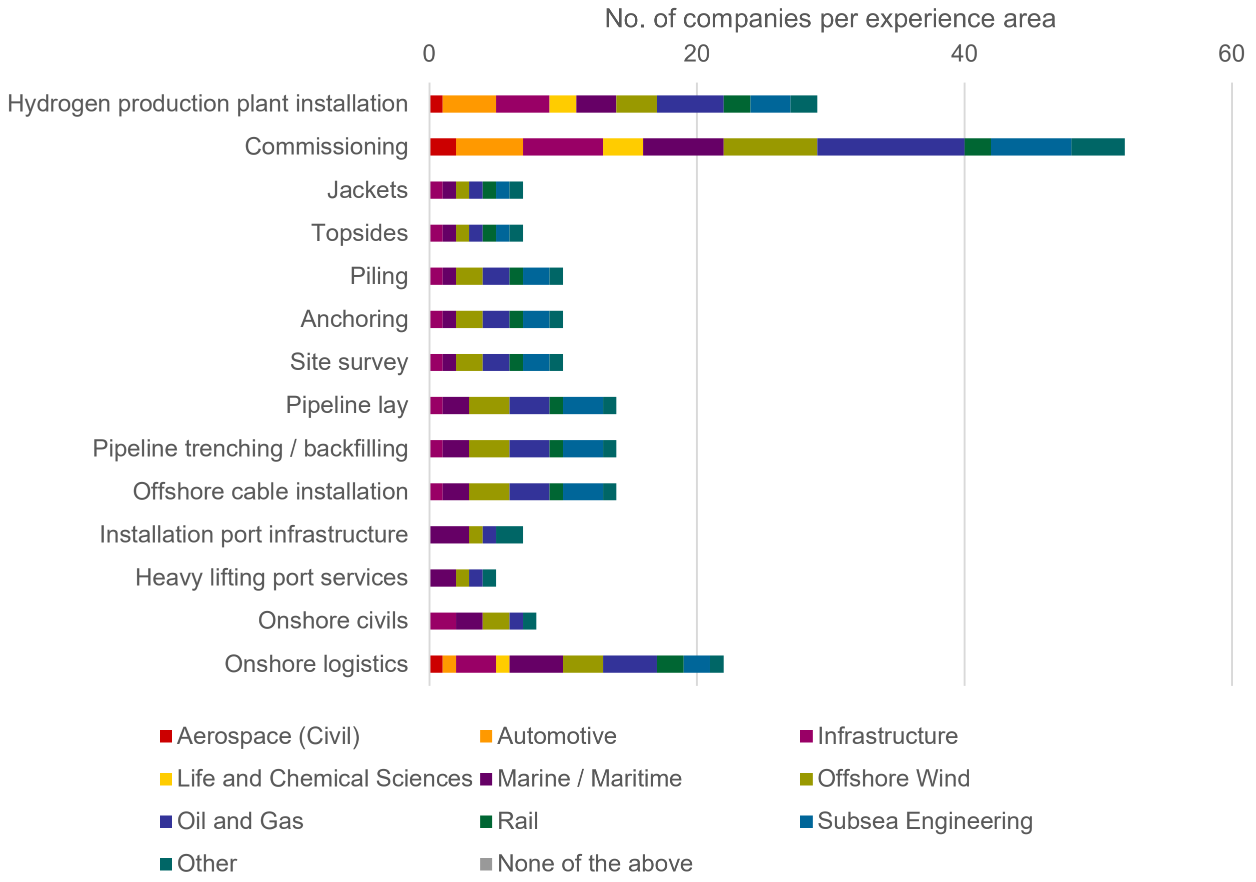


Figure 3.36 Number of companies per area of experience able or aiming to provide products/services to the Installation and Commissioning of Hydrogen Infrastructure stage of the hydrogen supply chain

3.4.2.4.4 Operation, Maintenance, and Decommissioning of Hydrogen Infrastructure

50 companies (~46% of survey respondents) expressed an ability or ambition to provide products/services in the 'Operation, Maintenance, and Decommissioning of Hydrogen Infrastructure' stage of the hydrogen supply chain. There are some gaps in the supply chain, notably in provision of crew transfer vessels (where supply capability certainly exists in parallel sectors) and pipelines to export hydrogen overseas. The rest of this supply chain stage, however, seems to have numerous companies offering services, particularly in training, inspection and repair of various pieces of infrastructure, and offshore decommissioning services.

Figure 3.37 shows the number of companies able or aiming to provide each of the service areas in this stage of the hydrogen supply chain according to how they perceive their involvement in the supply chain at large. Areas with a high proportion of companies that don't see themselves as involved can expose a weakness in the supply chain. For instance, offshore logistics seems to be a particularly underserved part of the supply chain with no companies offering services in CTVs or transport of hydrogen via subsea pipelines, and only one 'somewhat involved' company offering transport of hydrogen logistics via shipping services. On the other hand, areas with several highly or somewhat involved companies expressing an interest can be seen as a strength in the supply chain. Hydrogen plant and balance of plant maintenance and service are both areas with a strong offering, largely offered by the same 5 or 6 companies, as is Training.

Figure 3.38 shows the number of companies willing to supply each part of this stage of the supply chain according to the sectors in which they already have experience. Given that each service offering seems to attract interest from companies offering services across each of the experience areas, it seems that there is no one experience area that particularly lends itself to provision of operation, maintenance, and decommissioning services. Rather, knowledge and expertise from a range of parallel sectors can be leveraged and is transferable to this stage of the hydrogen supply chain.

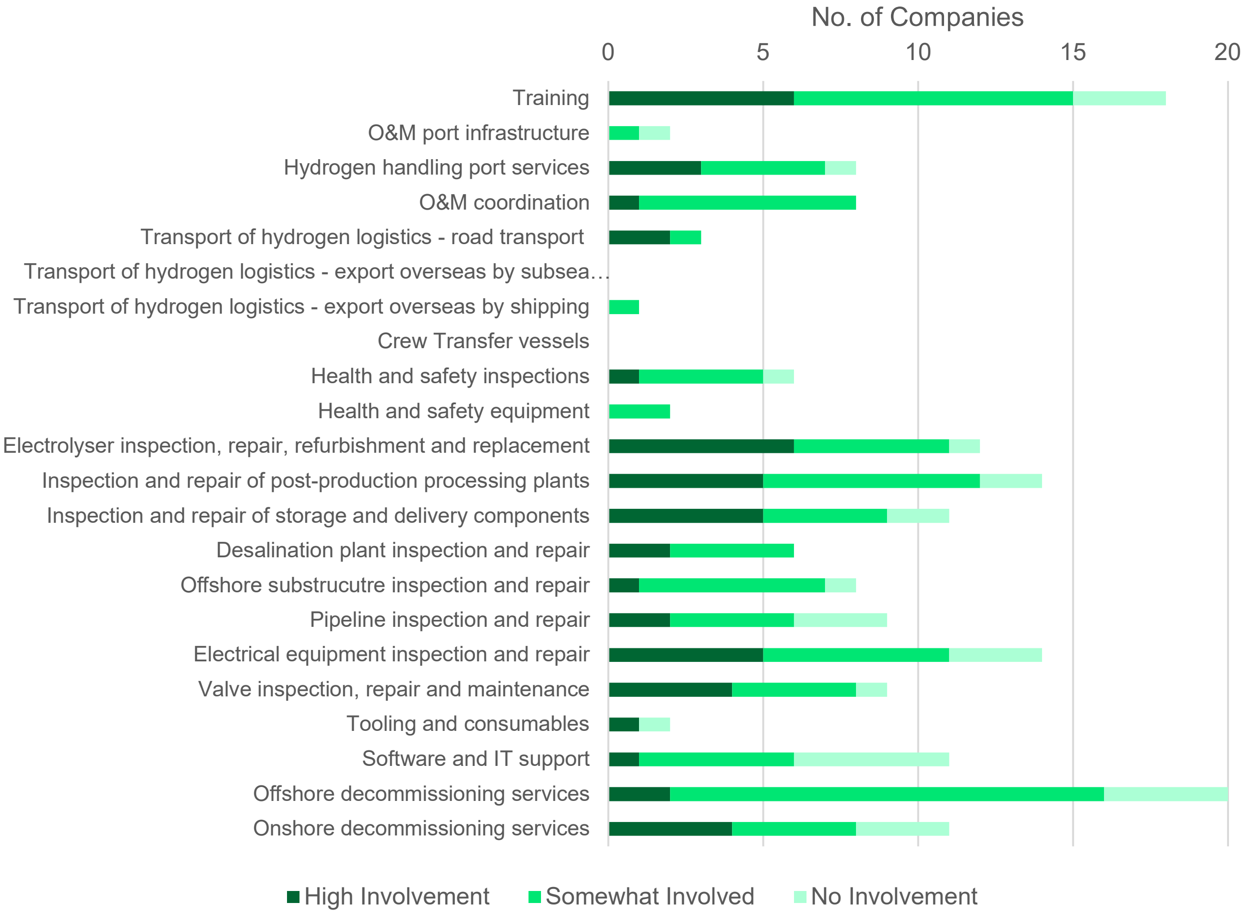


Figure 3.37 - Number of companies offering services in Operation, Maintenance, and Decommissioning of Hydrogen Infrastructure and their self-assessed current involvement in the hydrogen sector

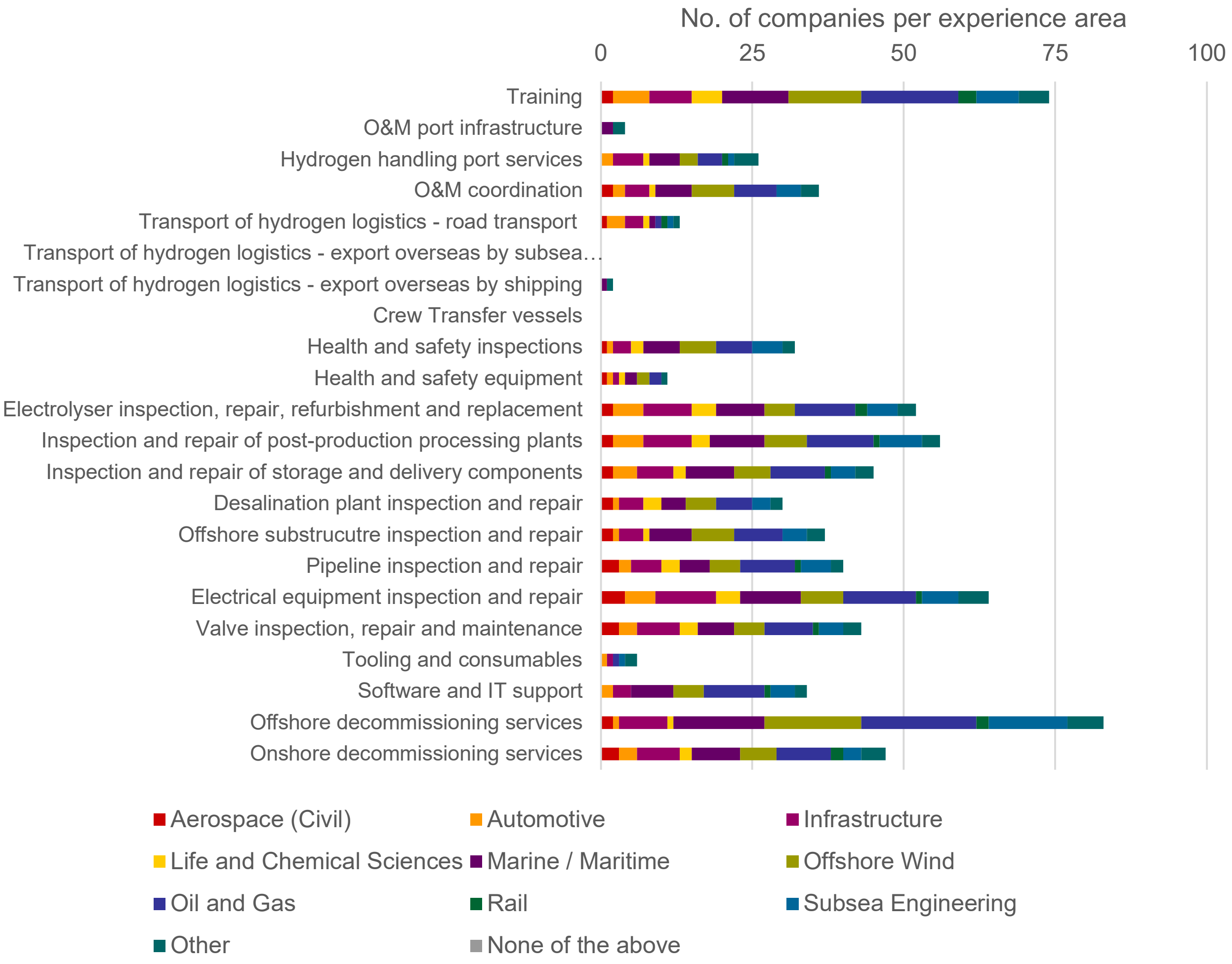


Figure 3.38 Number of companies per area of experience able or aiming to provide products/services to the Operation, Maintenance, and Decommissioning of Hydrogen Infrastructure stage of the hydrogen supply chain

3.4.2.4.5 Transport of Hydrogen

Transport of hydrogen is the supply chain stage with the lowest number of companies able or aiming to provide services, with only four companies expressing an interest.

Figure 3.39 shows the number of companies willing to offer various types of hydrogen transport and their perceived level of involvement in the hydrogen supply chain. No companies that are currently not involved in the supply chain have expressed a desire to enter it as a transport provider. While the number of companies express ability or interest in offering rail, tankers, and other seagoing vessels is limited, it is surprising that a greater number of companies do not offer trucking services. This might be a result of the survey not reaching a wider array of companies that might be able to offer these services.

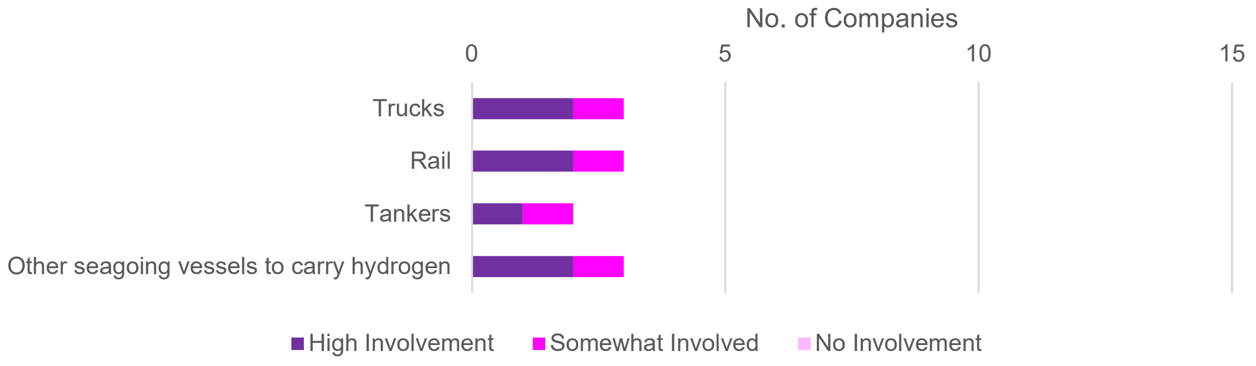


Figure 3.39 - Number of companies offering services in Transport of Hydrogen and their self-assessed current involvement in the hydrogen sector

Figure 3.40 shows the sectors in which the companies willing to offer transport of hydrogen services are currently active. These companies seem to be active in numerous supply chains, which may be a comment on the areas to which they offer transport services rather than areas in which they have particular expertise. For instance, they might offer vessels suitable for use in the offshore wind and oil and gas industries but would not otherwise be involved with these developments.

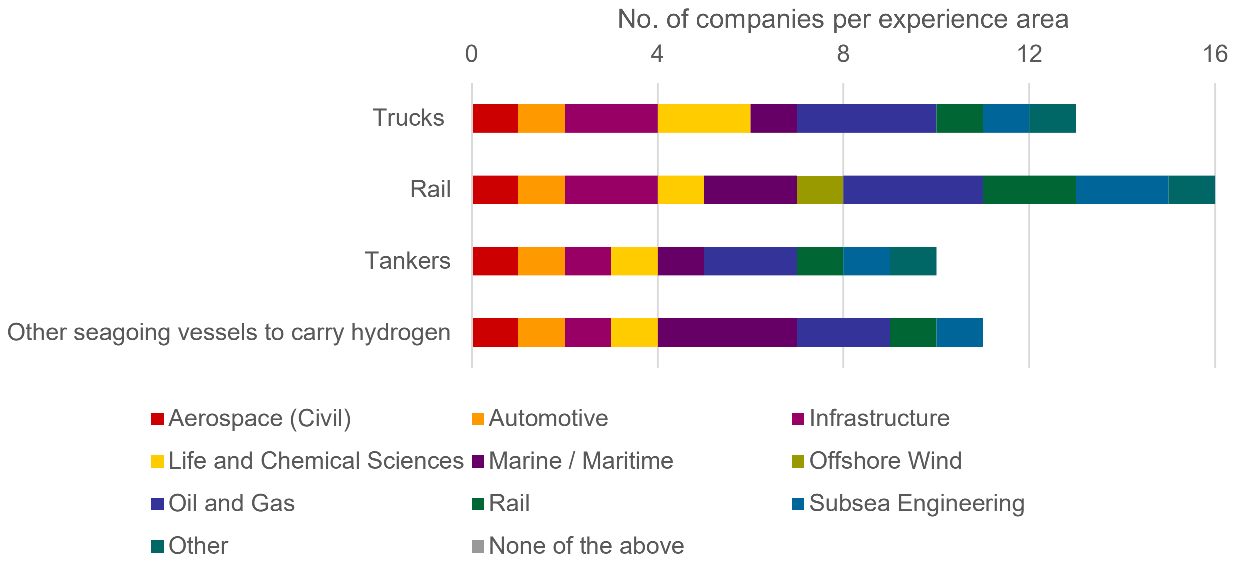


Figure 3.40 Number of companies per area of experience able or aiming to provide products/services to the Transport of Hydrogen Infrastructure stage of the hydrogen supply chain

3.4.2.4.6 Sector Support Functions

47 companies expressed an ability or ambition to offer sector support functions in the hydrogen supply chain.

Figure 3.41 shows the number of companies offering each type of sector support function as well as their perceived level of involvement in the broader hydrogen supply chain. The most serviced sector support function is Consultancy, with 34 companies (roughly one-third of survey respondents) offering this service. Of these, 28 consider themselves to be either highly or somewhat involved in the hydrogen supply chain, suggesting that the supply chain is particularly strong in this area. Health and Safety bodies are well represented, as are research from non-academic institutions. The number of universities offering services was surprisingly low, suggesting that better engagement is required to raise awareness of potential areas of collaboration. No further education colleges responded to the survey. As these are the institutions that may provide training and courses to enhance the skills of the future hydrogen workforce, better engagement may be required to notify them of the needs of the hydrogen sector and to encourage development of training materials ahead of when these skills are required.

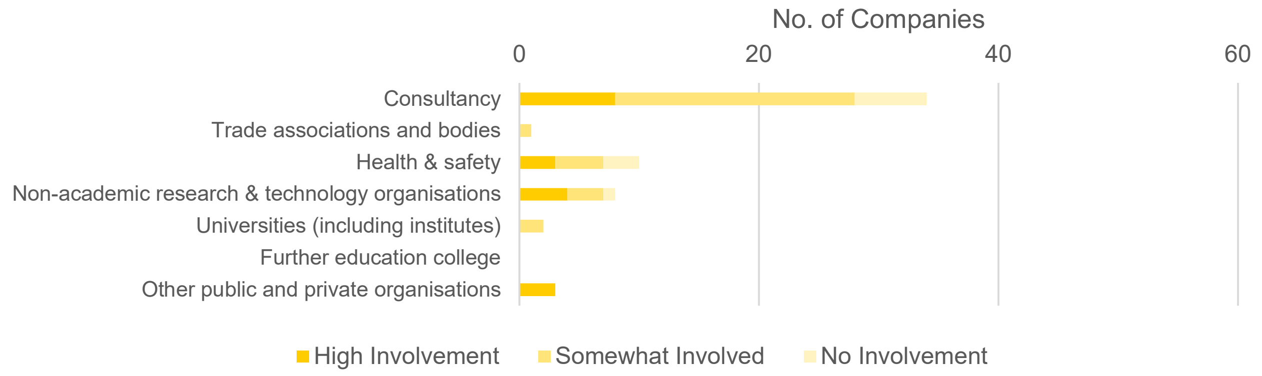


Figure 3.41 - Number of companies offering services in Sector Support Functions and their self-assessed current involvement in the hydrogen sector

Figure 3.42 shows the experience areas of companies offering sector support services. Given that each service offering seems to attract interest from companies offering services across each of the experience areas, it seems that there is no one experience area that particularly lends itself to provision of sector support services. Rather, knowledge and expertise from a range of parallel sectors can be leveraged and is transferable to this stage of the hydrogen supply chain.

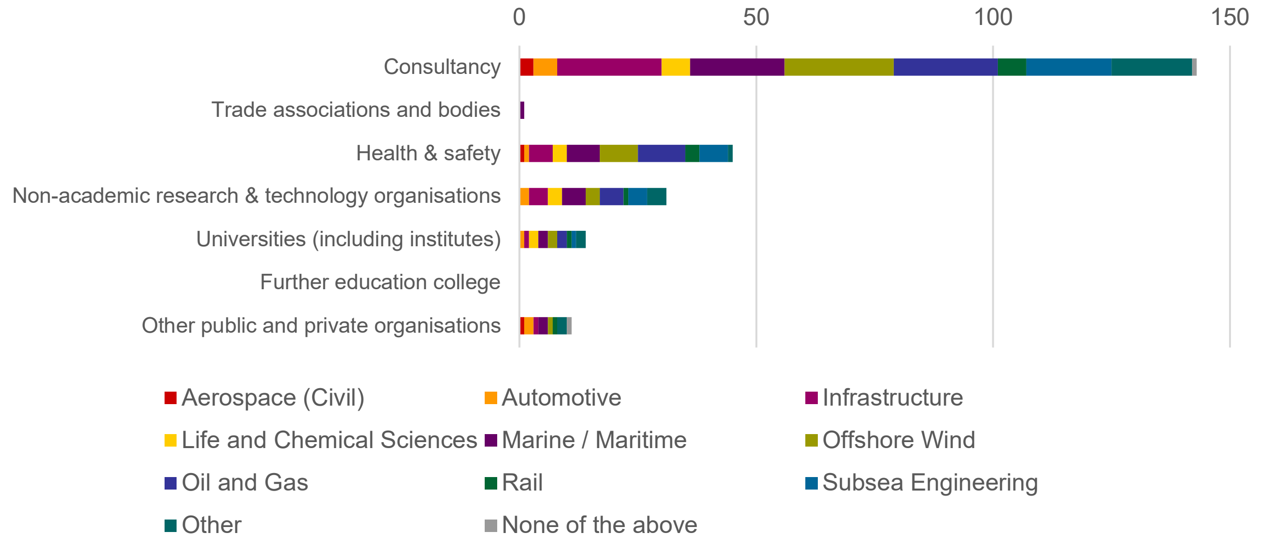


Figure 3.42 Number of companies per area of experience able or aiming to provide products/services to the Sector Support Functions stage of the hydrogen supply chain

3.5 Assessment of Supply Chain Opportunity

3.5.1 Wider Scottish Supply Chain Capability Analysis

This study also considered the Scottish supply chain beyond the responses that were received through the survey to provide a more complete picture of the wider capabilities of Scottish firms. To achieve this, the green hydrogen supply chain taxonomy categories were cross referenced against those of the other Scottish Industry Directories to ensure that any capability to supply from those parallel sectors had been considered. The Scottish Industry Directories considered were: Aerospace (Civil), Automotive, Infrastructure, Life and Chemical Sciences, Marine/Maritime, Offshore Wind, Rail and Subsea Engineering. While there is no distinct Scottish Industry Directory for the oil and gas sector, some key capabilities are captured in the Subsea and Marine directories.

The assessment of the different aspects of the Scottish green hydrogen supply chain considered the current Scottish capability to supply each secondary category of the taxonomy, appraised on a scale of high, medium and low. High capability in a secondary category represents direct experience or experience that is largely applicable to the green hydrogen supply chain across the constituent tertiary categories. Medium capability represents a mix of direct or similar experience in some tertiary elements, with limited experience in other tertiary elements. Low capability means that there appear to be limited similar experience found in the majority of tertiary elements from parallel sectors.

3.5.1.1 Development of Hydrogen Infrastructure

Table 3.6 Development of Hydrogen Infrastructure Supply Chain Analysis

Supply Chain Area	Scottish Supply Capability	Parallel Industry Directories	Comments
Concept engineering and consultancy	High	Offshore wind, subsea	Feasibility studies, as well as onshore and offshore surveys are regularly conducted in parallel sectors. Supply chain is likely very capable of performing similar role in the hydrogen sector.
Engineering, Procurement & Construction (EPC)	High	Offshore wind, subsea, infrastructure	Considerable experience overlap with offshore wind and subsea sectors in construction of offshore fixed and floating structures. Infrastructure sector has similar, strong capability in onshore civils.
Specialist hydrogen shipping design	Medium	Marine	Ship design capability within the Scottish marine supply chain. Minimal experience of design for hydrogen shipping.
Marinisation design	High	Offshore wind, subsea, marine	Scale of Scottish offshore sector industries likely to result in good capability in marinisation design of equipment.
Detailed component design	Medium	Offshore wind, subsea, life and chemical science	Overlap with current capability for pipeline, electrical system and control and safety design in subsea and offshore wind sectors. Companies within the life and chemical sciences sector may have capability to provide some of the hydrogen-specific components.

The development of hydrogen infrastructure capability shown in Table 3.6 predominantly consists of the design and engineering aspects of supply.

Generally, Scotland’s experience in offshore industries, including in the offshore wind, oil and gas, marine and subsea engineering sectors, means that there is already a relatively well-developed concept engineering consultancy and design supply chain ready to serve the hydrogen sector.

Specialist hydrogen shipping design is an area where capability may be lacking. Scotland has ship design experience, including experience in designing a hydrogen-fuelled vessel (Ferguson Marine’s involvement in the HySeas III project), but there appears to be a lack of existing supply chain capability in design vessels to transport hazardous substances.

Detailed component design is an area of mixed capability in the Scottish supply chain. There is some experience in pipeline, electrical system and control and safety design from the offshore wind, subsea and life and chemical science sectors. Bespoke hydrogen sector elements such as electrolyser design do not have clear parallels in these industries, however, the overlap in design and engineering skills may lead to capability being developed in the future.

Threats to the Scottish supply chain in these areas of limited current capability include specialist hydrogen shipping design being undertaken by current shipbuilding leaders, such as those in South Korea, China and Japan. Companies including Kawasaki Heavy Industries (Japan) and Global Energy Ventures (Australia) have already developed hydrogen shipping designs. The nature of the development of specialist hydrogen infrastructure also poses a potential threat as this supply does not require a local presence meaning that there are few obstacles to non-domestic suppliers providing strong competition to firms within the Scottish supply chain.

3.5.1.2 *Manufacture of Hydrogen Infrastructure*

Table 3.7 Manufacture of Hydrogen Infrastructure Supply Chain Analysis

Supply Chain Area	Scottish Supply Capability	Parallel Industry Directories	Comments
Marinisation of equipment	Medium	Medium, subsea	No explicit supply in parallel Scottish Industry Directories although capability likely inherent from Marine and Subsea sectors
Electrolysers	Low	Life and chemical science	Limited experience. Life and chemical science supply chain may also be able to support (e.g. manufacture of water purifiers) whereas the offshore wind supply chain can provide sensors.
Desalination plants	Low	Aerospace, subsea	Limited experience. Some components, such as valves, are already part of the aerospace and subsea supply chains. Hydrogen-specific components, such as reverse osmosis membranes may require capabilities not yet present in Scotland.
Compressors	High	Offshore wind, subsea	Companies already present and manufacturing these components in Scotland as part of the subsea supply chain.
Liquefiers & post-processing	Low	Life and chemical sciences	Limited experience. Reactors are already produced by the life and chemical sciences supply chain.
Tube trailers and storage tanks	Medium	Life and chemical sciences, subsea	Some capability from parallel sectors in valves and heat exchangers.
Offshore Structures	High	Offshore wind, subsea	Capability exists from serving parallel sectors, although strong competition from non-Scottish suppliers has limited recent Scottish opportunity.
Pipelines	Medium	Aerospace, subsea	Good capability in some areas of pipeline manufacture, such as valves and gaskets, whereas other areas, such as fabrication of the pipeline itself, are limited.
Electrical system	Medium	Offshore wind, subsea	The Scottish supply chain has some experience in control and monitoring, sensors and switchgear.
Health & safety and communications networks	High	Offshore wind, subsea	Capability in supplying IT networks and communications, fire and gas, ESD and control systems.
Bespoke manufacturing services	High	Infrastructure, aerospace, infrastructure, subsea, offshore wind	Considerable experience in precision machining, in particular.

The manufacture of hydrogen infrastructure primary category considers the capability of the Scottish supply chain in the production of components for the green hydrogen industry.

Scottish suppliers have good capability to supply in some elements, including compressors, offshore structures, health and safety systems and bespoke manufacturing services, because of their existing overlaps with other industry sectors.

The Scottish supply chain's existing weaknesses in competitive manufacturing are revealed by the low number of companies with recent capability and experience in pipeline and offshore structure fabrication, where most of this kind of work is undertaken in England or outside of the UK because of cheaper costs. The requirements of manufacturing hydrogen-specific components may also be an obstacle where there is low capability in manufacturing components for liquefiers and post-processing, and in desalination plants. For the latter, the experience and capability to provide generic components such as valves is strong, but this is counterbalanced by the absence of manufacturing of specialist components. The lack of capability to manufacture specialist components is in part related to immaturity of the green hydrogen sector where it is challenging to ascertain potential future capability.

The lack of capability and experience in manufacturing is a threat to the future supply chain where other markets already have a comparative advantage through their existing manufacturing sectors. Simple manufacturing, as required for elements of pipelines and offshore substructures in the offshore wind and subsea sectors, is often done outside of Scotland by companies in Northern Europe or East Asia. This is unlikely to change without considerable support for Scottish industry that would make it more competitive on price.

Other countries have already developed their hydrogen-specific supply chain capability, particular competition should be expected from China, Japan, Germany and USA as they already have hydrogen infrastructure deployed whilst also already having considerable manufacturing expertise. Of particular note within the UK, ITM Power is rapidly emerging as a major electrolyser developer and manufacturer, but has no current presence in Scotland.

3.5.1.3 Installation and Commissioning of Hydrogen Infrastructure

Table 3.8 Installation and Commissioning of Hydrogen Infrastructure Supply Chain Analysis

Supply Chain Area	Scottish Supply Capability	Parallel Industry Directories	Comments
Hydrogen production plant installation	Medium	Infrastructure	Little direct overlap with parallel industry directories, although some experience in Scotland likely in plant commissioning.
Offshore structures installation	High	Offshore wind, subsea	Direct experience of this within the Scottish supply chain from parallel sectors.
Offshore cable installation	High	Offshore wind	Direct experience from parallel sectors.
Pipeline installation	High	Subsea	Direct experience from parallel sectors
Ports installation	Medium	Marine, offshore wind, subsea	Direct experience from parallel sectors
Onshore works	High	Infrastructure	Large number of civil engineering firms present in the infrastructure supply chain.

The Scottish supply chain has strength where capabilities from parallel sectors can be easily applied to the green hydrogen industry. Offshore structure, pipeline and cable installation are already integral parts of the requirements of the offshore wind and subsea sectors and the Scottish supply chain has evolved to meet this demand. From the infrastructure sector, there is also many firms who would be able to conduct onshore works. The similarity and direct experience of these processes means that it would be easy to transfer these skills to a green hydrogen context.

The capability of installation ports to meet the heavy lifting needs is an area that could be improved upon; capability is limited to certain locations across Scotland, but targeted investment could rectify this and provide good capability across the country. Conversely, Scottish installation ports are already under pressure from better equipped, foreign competitors in the offshore wind sector and failure to make investments in the necessary equipment could see Scottish ports bypassed by the green hydrogen sector in future, especially since installation and commissioning does not require a continued local presence.

Although several elements are strengths in this supply chain area, supported by Scotland’s experience in the offshore wind and subsea sectors, there are threats from neighbouring markets that currently have the same expertise and interest in offshore wind and subsea engineering. For example, Norway’s similar long history in the subsea sector means that their supply chain could feasibly present a strong challenge to Scottish companies if they innovate based on their current experience.

3.5.1.4 Operation, Maintenance and Decommissioning of Hydrogen Infrastructure

Table 3.9 Operation, Maintenance and Decommissioning of Hydrogen Infrastructure Supply Chain Analysis

Supply Chain Area	Scottish Supply Capability	Parallel Industry Directories	Comments
Training	High	Life and chemical sciences, subsea, offshore wind	Well-developed training and education sector. Potential to develop strong capability to provide training.
Ports operations	Medium	Marine, subsea, offshore wind	Extensive port infrastructure capable of handling operations and maintenance. Supply chain experience with oil and gas may also mean potential capability with hydrogen, but no direct hydrogen handling experience.
Onshore logistics	High	Marine, subsea, offshore wind	Extensive operations and maintenance experience. Direct experience of hydrogen road transportation in Orkney as part of Surf ‘n’ Turf/BIG HIT.
Offshore logistics	Medium	Marine, subsea	Only capability comes from experience acquired through oil and gas shipping. Minimal direct hydrogen experience of this kind.
Health and safety	High	Offshore wind, subsea	Direct experience from offshore wind and subsea sectors.
Hydrogen plant maintenance and service	Medium	Subsea	Inspection and repair experience of oil and gas installations will lend some capability. Well-developed O&G plant inspection supply chain already exists but experience of maintaining hydrogen-specific components yet to be established.
Balance of plant maintenance and service	High	Offshore wind, subsea	Direct experience of and well-developed supply chain for pipeline, electrical equipment and valve inspection and repair from parallel sectors.
Operations and maintenance support	High	Offshore wind, subsea	Software and IT support is already an integral part of parallel sectors.
Offshore decommissioning services	High	Offshore wind, subsea	Well-developed supply chain, in response to growing demand from oil and gas industry.
Onshore decommissioning services	High	Infrastructure	Well-developed supply chain in civils.

Operations, maintenance and decommissioning of hydrogen infrastructure is an area of relative strength for the Scottish supply chain. Overlaps with the offshore wind, subsea and marine sectors mean that the supply chain for most of the secondary categories is potentially well-developed. The particular areas of strength include training, health and safety, balance of plant maintenance, onshore logistics, O&M support, and decommissioning.

The supply chain categories that require further capability development are in offshore logistics and hydrogen plant maintenance and service. These categories require experience with hydrogen-specific equipment and processes that are not yet commonplace, including transport of hydrogen logistics for the former and electrolyser inspection, repair, refurbishment and replacement for the latter. However, it is likely these services would be developed in Scotland in response to future project demand as there is logic to having these supplied locally.

The current advantage of the Scottish supply chain's experience in operations, maintenance and decommissioning in parallel sectors presents an obvious opportunity for transition to future capability in the hydrogen sector. The investment required to make the transition is likely to be relatively minimal because of the similarity of the required services.

3.5.1.5 Transport of Hydrogen

Table 3.10 Transport of Hydrogen Supply Chain Analysis

Supply Chain Area	Scottish Supply Capability	Parallel Industry Directories	Comments
Road transport delivery	Medium	-	Direct experience of hydrogen road transportation in Orkney as part of Surf 'n' Turf/BIG HIT.
Shipping delivery	Low	-	No evidence of Scottish capability in this field.

Capability for road transport is scored as medium due to the experience of the Surf 'n' Turf/BIG HIT project in Orkney. There is no clear suggestion of capability from parallel sectors

There is minimal experience of shipping hydrogen in Scotland. Surf 'n' Turf currently transports hydrogen from Eday to Kirkwall, but this is done by road tankers on commercial ferries, which does not meet the taxonomy criteria.

The proximity of Scotland to competitor markets can be interpreted as both a supply chain opportunity and a potential threat. Hydrogen shipping companies, in particular, would not need to operate from Scotland or with a Scottish fleet in order to meet the supply requirement.

3.5.1.6 Sector Support Functions

Table 3.11 Sector Support Supply Chain Analysis

Supply Chain Area	Scottish Supply Capability	Parallel Industry Directories	Comments
Professional services	High	Offshore wind, subsea, infrastructure, life and chemical sciences, marine	Well-developed supply chain for a variety of professional services. Services already being provided to hydrogen sector.
R&D and education	High	Offshore wind, subsea, infrastructure, life and chemical sciences, marine	Scottish universities and research institutes already engaged in hydrogen-specific research. Supply chain has strong capability in this area.

Scotland has a very well-developed sector support supply chain with a full range of professional services being provided to parallel sectors, as well as to the green hydrogen sector. Experienced consultancy services are provided by multiple organisations and Scotland already has its own hydrogen industry trade association in the form of the Scottish Hydrogen & Fuel Cell Association (SHFCA).

The Scottish education and research sector is similarly well-developed and is already engaged in hydrogen research, such as the University of Edinburgh's HyStorPor project. The Scottish sector support supply chain is well placed to export this knowledge and capability to projects in other markets where physical presence may not be necessary to fulfil roles in this area. Similarly, failure to innovate and keep required capability in Scotland in future could also see sector support functions being carried out from outside the country. It is reasonable to assume that areas with rapidly developing hydrogen sectors, such as Japan, Australia, Germany and California, will also have increasingly well-developed sector support supply chains that could provide strong competition to the Scottish supply chain.

3.5.2 SWOT analysis

3.5.2.1 Strengths

Despite the infancy of the Scottish green hydrogen sector, its potential supply chain has several possible areas of strength. The green hydrogen supply chain has considerable overlap with elements of parallel sectors, most notably, the oil and gas, offshore wind and subsea engineering sectors.

The current strengths of the Scottish supply chain capability to support a potential future green hydrogen project are in areas of project development, installation, O&M and sector support where these can easily come from Scottish companies experienced in similar industries.

The strengths in the development of hydrogen infrastructure are in concept engineering and consultancy, EPC services and marinisation design. Here there are strong parallels with the established oil and gas, infrastructure, marine and subsea engineering sectors.

There are several strengths identified in the installation and commissioning of hydrogen infrastructure, notably in offshore structure, cable and pipeline installation that area key areas of the offshore wind and subsea engineering sectors.

In the O&M of hydrogen infrastructure, experience from the oil and gas, offshore wind and subsea engineering sectors in tertiary categories such as training, health and safety, and onshore and offshore decommissioning, means that a high level of capability already exists across the Scottish supply chain.

The Scottish supply chain is well placed to provide sector support functions to the green hydrogen sector based on high representation of consultancies, trade associations and research organisations with the capability to support industry growth. Many of these organisations are active in supporting sector development.

3.5.2.2 Weaknesses

Gaps in the Scottish supply chain are predominantly in supply areas bespoke to the design, manufacture and maintenance of hydrogen generation plant, where few companies have had the opportunity to gain direct experience to date. As with any nascent industry, supply for early projects is expected to come from companies operating in relevant parallel sectors. While there are several links between the potential hydrogen supply chain and those of similar industries, the supply of many products and services in those sectors are also non-Scottish.

Although the Scottish supply chain has some capability in component manufacturing and fabrication, this is seen to be weaker in supply areas that are bespoke to hydrogen generation infrastructure. Experience from supply to similar industries suggests many Scottish fabrication companies are less competitive on cost than non-Scottish suppliers and so it may be challenging to convert this into an area of strength.

Transportation of hydrogen appears to be an area with limited Scottish supply capability. Supply would be likely to come from companies with experience in the movement and handling of hazardous substances. However, this was the supply area with the fewest survey responses and no clear overlap with established supply capability from parallel sectors.

3.5.2.3 Opportunities

Opportunities exist where supply chain strengths can be leveraged. For the Scottish supply chain this will depend on the scale of the sector and may depend on whether the projects they are supplying to are in the domestic or export markets.

For domestic hydrogen projects there is a strong logic of local supply in inspection, maintenance and repair services as mobilisation costs offshore are significant, especially for pre-commercial projects. Local capability, vessels, and project management know-how is typically the most cost-effective solution. If a strong Scottish hydrogen sector develops then Scottish O&M suppliers will have a significant opportunity to benefit.

There are also opportunities for Scottish suppliers based on experience within the local supply chain where competitive advantage isn't based on location. This is applicable to elements of project development, such as hydrogen sector design and engineering, and many of the sector support functions. Where Scottish supply does exist, it is likely that developers will consider this a good opportunity for increasing local content.

There will also be opportunities in export markets where there is Scottish supply capability in areas that have no significant logistical benefit from using local supply, or where there are few logistical barriers to Scottish companies supplying oversees. In the manufacture and installation of hydrogen generation infrastructure and balance of plant Scottish companies will compete on an open market basis, relying on their track record and commercial offering. Where Scottish companies are experienced and can compete on quality, opportunities may open up in export markets if they can achieve attractiveness on cost.

Where there are gaps in the supply chain a significant hydrogen market could create an opportunity for investment in new capability to meet demand. A high requirement for hydrogen generation plant could attract a supplier to establish an indigenous pipeline manufacturing and associated hardware capability supply in Scotland, with good pan-European supply potential.

3.5.2.4 Threats

Some threats to the Scottish supply chain can be seen as the opposite of the opportunities, where established supply chains in competing markets take advantage of low barriers to supplying Scottish projects or have stronger experience and track record than Scottish suppliers.

The Scottish supply chain is particularly exposed to competition from stronger markets in manufacturing, where established fabricators in Europe can be more competitive on price whilst avoiding significant logistics costs or where hydrogen-specific manufacturing expertise is established outside of Europe. Should those countries also establish strong domestic markets then stronger supply chains for subcomponents and centres of excellence will likely appear around key infrastructure suppliers.

The prevailing threat to the Scottish supply opportunity may be in the lack of hydrogen generation projects being developed. The timescale for deployment of projects is less than certain and several years away. While the lack of current developments means there are limited opportunities for Scottish companies to demonstrate capability and develop track record, continued uncertainty over future project pipeline may deter suppliers from investing in facilities and technology and may inhibit supply chain diversification into the sector.

3.5.3 Summary

A database has been established of around 100 Scottish companies active in, or with an expressed interest in entering the green hydrogen sector.

- There is considerable hydrogen supply chain overlap with elements of parallel sectors, most notably, the oil and gas, offshore wind and subsea engineering sectors.
- The current strengths of the Scottish hydrogen supply chain are in the areas of project development, installation, Operations & Maintenance and sector support where these capabilities can be transferred from Scottish companies with experience in similar industries.

- Gaps in the Scottish supply chain are predominantly in supply areas bespoke to the design, manufacture and maintenance of hydrogen generation plant.
- Transportation of hydrogen appears to be an area with limited Scottish capability.
- The prevailing threat to the Scottish supply opportunity may be in a low pipeline of hydrogen generation projects.
- Established supply chains in competing markets may take advantage of low barriers to supplying Scottish projects or have stronger experience and track record than Scottish suppliers.

The Scottish supply chain is well positioned to support, and ultimately to benefit from, the development of green hydrogen. However, a steady pipeline of hydrogen developments over the next decade will be essential to ensuring the development of an indigenous supply chain so that Scotland is ready to deliver and take advantage of full commercial deployment.

3.6 Socioeconomic Assessment of Scotland’s Green Hydrogen Potential

3.6.1 Introduction

For this high-level analysis, the socio-economic impact framework used in the Sectoral Marine Plan was selected (summarised in Table 3.12). This framework of 15 indicators allows for assessment of the likely socio-economic impacts a development might have on an individual level, at a community level, and at a wider political and environmental level. This framework was selected as the three categories of fifteen indicators allows for a high-level but comprehensive socio-economic assessment (in line with the scope of this project) and it closely aligns with indicators used in the Scottish Government’s National Performance Framework (NPF). This latter quality is desirable as the NPF is used to measure Scotland’s progress towards achieving national values and outcomes and any policy that will improve performance will likely be looked upon favourably by policymakers and decision-making bodies. Demonstrating benefits according to indicators that align with the NPF is therefore beneficial to all sectors in Scotland as this can help show to what extent sector aims align with broader policy goals.

Table 3.12: Summary of Sectoral Marine Plan socio-economic indicators used in this assessment

	Social Indicator
Individual	Family, family life, and inter-generation issues
	Jobs, career, and employment
	Money and cost of living
Community	Local jobs, local industry, and community sustainability
	Transport connections and technology connections
	Education
	Shops and housing
	Socialising, recreation, parks, and leisure
	Friends, being involved, and supporting others
	Local identity, cultural heritage, and Gaelic
	Healthcare
	Connection to nature and landscape
	Local political and decision-making systems
Wider political and environmental context	Landscape, seascape, wildlife, and environmental change
	National and EU level political and decision-making systems.

3.6.2 Assessment

In this high-level assessment, the impact of developing green hydrogen is considered against each of the three clusters of indicators (see Table 3.12 for details). For each indicator, the likely impacts (both positive and negative) are discussed, drawing on insights from in-house expertise and available case studies.

3.6.2.1 Socio-economic impacts on Individuals

Individuals are likely to experience net positive socio-economic impacts as a result of green hydrogen development. These will primarily stem from the creation and retention of high-quality jobs. Jobs are likely to be created directly in the development and operations of both offshore wind farms and hydrogen production and transport facilities, and indirectly in the supply chain at large, as greater demand must be met with greater supply. Indeed, jobs are already being created. EMEC has developed in-house hydrogen expertise after investing in an electrolyser in 2015, which has since been used to produce the world's first tidal-powered hydrogen. It has also facilitated EMEC partnering in a project – announced in 2018 – developing an all-in-solution to clean predictable energy generation, grid management, and production of hydrogen using excess capacity. As hydrogen gains prominence as an energy source, it is likely to be met with further role creation in policy also. For instance, the Orkney Islands Council has a dedicated Hydrogen Officer role which has been created as a result of local hydrogen developments such as the Surf 'n' Turf project. Jobs have also been created through the establishing of a specific hydrogen business unit in EMEC. Hydrogen developments in other councils would likely see the creation of similar roles.

The creation of high-quality jobs can have a positive impact on 'Family, family life, and inter-generation issues' in a number of ways. First, children stand to benefit from an increased standard of living as a result of their parents earning higher wages. Depending on the prior circumstances of their parents' employment, this can have a positive impact on reducing child poverty and will generally result in improvements to child wellbeing. Second, many green hydrogen roles are likely to be created in remote, rural/coastal communities as these are often located close to better wind resources. Families in these communities can sometimes suffer as a result of family members having longer commutes to work or even having to migrate away from the area in search of employment opportunities. The creation of local roles can therefore have a positive impact through reduced commuting times (resulting in more free time for individuals that can be spent with loved ones) and through allowing individuals to remain close to family in the area e.g. grandparents.

As well as creating new jobs, green hydrogen developments could result in improved job retention through companies and their employees entering into the supply chain from parallel sectors, such as oil and gas. With dwindling North Sea oil and gas reserves and market demand as economies move towards net zero, long-term jobs in the oil and gas industry are declining and at risk. However, the knowledge and skills from this sector are transferable to other industries in the offshore energy space, including offshore wind and hydrogen. The development of green hydrogen from offshore wind therefore provides an avenue for workers to continue to use and develop skills learned from oil and gas, in line with just transition principles. It is important to note that this will not only affect workers employed directly by the oil and gas industry but will also provide a new source of income for the wider supply chain, including more service-based occupations such as consultancy.

Furthermore, the development of green hydrogen will provide a new source of income and need for services from ports. Not only will ports be required in the construction and installation of green hydrogen developments, but they could increasingly be used for green hydrogen exports to neighbouring markets and, potentially, for refuelling of ships, once hydrogen-powered shipping technology reaches maturity. Depending on demand, this could provide an additional source of income and employment opportunities for existing ports and could even require the development of new ports in more strategic locations for this new industry sector. As many Scottish ports have faced economic hardship following industrial decline, this could provide an avenue for alternative employment for remaining staff that allows them to continue to use and build upon skills developed thus far in their careers.

Regarding money and cost of living, job creation normally has a positive impact for individuals. However, it is important to take the baseline into consideration when determining if this is the case. While high-quality, well-paying jobs are expected from the development of green hydrogen, it is possible that these will not offer the same level of pay as could be expected in some parallel industries e.g. oil. Workers transitioning from oil into green hydrogen may experience a reduction in income, despite securing a high-quality job. For most new entrants to the sector, however, this is unlikely to be the case and will be experienced as a positive development. Cost of living is assumed to be largely unaffected, though there is a risk that it may rise slightly should the costs of new hydrogen technologies and infrastructure be passed onto consumers.

3.6.2.2 Socio-economic impacts on Communities

This section considers the likely impacts (both positive and negative) of green hydrogen developments on each of the ten Community indicators (see Table 3.12 for details), with each indicator considered in turn.

Green hydrogen developments are likely to have a positive impact on local jobs, local industry, and community sustainability. Local companies active in the green hydrogen supply chain could directly benefit from increased demand for their products/services. The retention and creation of high-quality, well paid jobs could positively benefit the broader local economy through increased local spend resulting from more disposable income. The local economy might further benefit from increased community sustainability (and hence a larger local market) that could result from local green hydrogen developments. For one, the creation of local jobs could result in a net inward migration to remote and rural areas and long-term, high-value jobs might incentivise families to settle. For another, new opportunities might facilitate increased population retention, with fewer people having to leave the community in search of employment elsewhere. As many communities are based around dominant industries, the development of green hydrogen projects in places based around parallel sectors (e.g. oil and gas) could have a particularly strong positive impact as these industries decline. Without viable alternatives, such communities can be entirely decimated, as happened in the 1980s following the closure of British coal mines. This would be entirely contrary to Just Transition principles.

The impact of green hydrogen projects on local transport connections and technology connections is likely to be minimal. Greater traffic congestion might result from greater travel to and from a site or an increased workforce. Any negative impacts, on either technology or transport connections, can be mitigated with advanced investment to expand local capacity.

The development of a new industry, such as green hydrogen, will likely have a positive impact on education within communities. For instance, universities, colleges, and further education facilities will have the chance to develop and enhance their course offerings to ensure students are gaining the necessary skills. Furthermore, through use of apprenticeships and training facilities, companies can enhance the skills of their workforce. For more rural and remote communities, improvements in community sustainability (as detailed above) and especially a growth in the number of local children could lead to greater support being offered for local schools as a result of the increase in demand for their services.

Local shops are likely to benefit from green hydrogen developments through introduction of new customers (if a site was previously unused) and through increased disposable income of existing customers (should they benefit from new employment opportunities).

Green hydrogen developments could positively impact both ‘Socialising, recreation, parks, and leisure’ and ‘Friends, being involved, and supporting others’. As mentioned before, the development of industries in rural, remote communities (where natural resource might be well-suited for green hydrogen developments) can result in net inward migration and improved population retention. This can result in the maintenance and development of strong bonds and relationships within the community. The larger population can also mean that recreation, parks, leisure, and other venues for socialising are used by more people.

Communities with an industrial heritage and historic links to offshore energy will likely benefit from green hydrogen as it reinforces a key aspect of local identity. The benefits will be particularly acute in areas that have suffered recent industrial decline, especially if residents are supported to gain the skills necessary to participate in the nascent green hydrogen sector. Outwith the Western Isles, green hydrogen developments are unlikely to have much of an impact on Gaelic. For Gaelic speaking regions, there is a risk that a large inward migration of non-speakers could reduce use of the language. However, should new families settle as a result of high-quality employment opportunities, it is possible that children will learn the language at school and from classmates.

Greater employment from green hydrogen developments is likely to have a positive impact on the physical and mental wellbeing of those employed and their dependents. Furthermore, the transition to green hydrogen and the use of hydrogen-powered vehicles is likely to have a positive impact on health through the reduction of harmful emissions.

The development of wind to green hydrogen systems in Scotland is likely to minimally impact people’s connection to nature and landscape. While the development of new offshore windfarms could meet with local opposition on visual pollution grounds, this is likely to be much lower than resistance faced by onshore wind as the wind farms are much more remote.

The extent to which local political and decision-making systems are impacted through the unlocking of Scotland’s green hydrogen potential depends, in part, on the manner and extent to which stakeholders are involved. Community energy projects, for instance, can result in the formation of new community-based decision-making bodies. In his 2019 paper ‘*Winds of change: Legitimacy, withdrawal, and interdependency from a decentralized wind-to-hydrogen regime in Orkney, Scotland’*, Michael Westrom examined the impact the Surf ‘n’ Turf project had had on local governance. The community-owned wind turbine earns revenue for the Shapinsay Development Trust and the distribution of this income “is capable of adding to, replacing, and shaping expenditures and policies enacted by local government”.

3.6.2.3 Socio-economic impacts on the Wider Political and Environmental Context

The unlocking of Scotland’s green hydrogen potential should significantly benefit efforts to reduce greenhouse gas emissions and contribute to global climate change mitigation targets.

Green hydrogen in Scotland has the potential to develop and enhance Scotland’s international reputation as a world-leader in renewable energy, with significant potential for export of goods and services to other interested regions.

3.6.3 Summary

Unlocking Scotland’s green hydrogen potential could result in numerous benefits at an individual, community, and wider political and environmental context. The main benefits are likely to result from job creation. In particular, jobs that are accessible to oil and gas and ports workers with transferable skills and experience will help prevent many of the negative impacts that would otherwise arise as a result of dwindling North Sea oil and gas reserves and market demand as economies move towards net zero. This is crucial for a just transition away from fossil fuels to be achieved. Likewise, the creation of high-quality, well-paying jobs in green hydrogen developments and the wider supply chain can encourage inward migration to an area or better population retention, as residents need not leave in search for work. This will be of particular benefit in remote, rural communities that have experienced shrinking populations as a result of the decline of industrial and more traditional industries.

Communities will also benefit from job creation as this will have concomitant benefits for local supply chain companies as well as local businesses that will benefit from the custom of a secure and growing workforce. The increased use of hydrogen as a fuel will likely have wider health benefits for communities due to reduced vehicle emissions and this in turn may encourage greater use of the outdoors for leisure and recreation, though this is likely to be minimal. If green hydrogen developments are located in areas formally dedicated to oil or gas processing, then this will have a positive impact on community stability as the workforce could be able to transition or grow, rather than having to leave to find work elsewhere should existing jobs decline. This could in turn bolster any sense of local identity rooted in an industrial past and heritage.

On a broader scale, the development of green hydrogen in Scotland could have a significant impact in Scotland’s role in reducing greenhouse gas emissions and could benefit Scotland’s international reputation as a leader in climate change action. Commitment to tackling emissions in heat and transport (following successful decarbonisation of the electricity sector) would demonstrate true commitment and leadership, which will be imperative for a successful COP26 in Glasgow in November 2021. There is also the potential for Scotland to become exporters of green hydrogen knowledge and technology, enhancing Scotland’s international reputation as well as generating revenue that might be used to the benefit of all Scottish citizens e.g. through increased public spending or reduced tax rates.

4 MODELS FOR GREEN HYDROGEN PRODUCTION

4.1 Introduction

A techno-economic cost model developed by Xodus has been used to analyse various models for green hydrogen production from offshore wind in order to understand what the key influencers are when calculating the Levelised Cost of Hydrogen (LCoH) from Scotland's offshore wind farms.

The model considered the main techno-economic drivers of CAPEX and OPEX, as well as different components required for the hydrogen production process to become the most cost-effective, including (but not limited to) electrolysers, compressors, and storage vessels. The model included cost reduction projections of the main components to evaluate how the production cost (in £/kg) is likely to reduce over time.

The model is flexible to accommodate any future adaptations and upgrades to incorporate different sites, emerging technologies and cost reduction curves of each component, so it can be compared to other models domestically and internationally.

The model was delivered in Excel to allow user interactions as required. Building the model in Excel also enables the user to use this tool after the delivery of the project, without licensing issues or server maintenance fees.

This chapter also elaborates on the current policy landscape and identifies any existing or potential incentive mechanisms to enable a wider deployment of green hydrogen technology in Scotland.

The cost of producing, storing and delivering green hydrogen to the end-user is not likely to be cost competitive with the current use of fossil fuel technologies on purely cost vs cost basis. Therefore, this chapter also identifies the most promising incentive mechanisms to enable green hydrogen to compete with other fuels. This was supported by assessing the policy landscape of other hydrogen leading markets, such as Germany, the Netherlands, Australia, or Japan.

As a part of the policy focused section, a carbon intensity assessment was considered. The carbon intensity assessment, (also referred to as emission abatement potential), of each sector that could be served by green hydrogen in the future. Hydrogen could replace different types of fossil fuels across various energy sectors – road transport, low-grade heat, industrial heat, chemical feedstock, electricity, shipping or aviation. Each of the sectors use different fuels and technologies with different efficiencies. Therefore, the carbon intensity assessment identified what the carbon price would need to be for green hydrogen to compete with traditional technologies that use fossil fuels.

4.2 Levelised Cost of Hydrogen Model

A levelized cost of hydrogen (LCoH) model was developed to understand the key drivers in the cost of green hydrogen generation from offshore wind. The LCoH, defined by Equation 1 below, is a metric used to define the costs of hydrogen production over the lifetime of the assets, similar to levelized cost of electricity often used in the renewables industry.

$$LCoH = \frac{NPV\ CAPEX + NPV\ OPEX + NPV\ TRANSPORT\ COSTS}{NPV\ Hydrogen\ production} \tag{1}$$

The model was built to enable comparison of three key scenarios for green hydrogen generation from wind. These three scenarios, and the relevant variables and assumptions were agreed upon in a workshop with the full project consortium.

Three production models were analysed as agreed with study partners at the commencement of the study:

1. Scenario 1: Small-scale pilot project for green hydrogen production from offshore wind;
2. Scenario 2: Commercial scale offshore wind farm coupled with onshore hydrogen production;
3. Scenario 3: Commercial scale offshore wind farm coupled with offshore hydrogen production.

Scenario 1 – Small-scale pilot project for green hydrogen production from offshore wind.

Scenario 2 – Commercial scale offshore wind farm coupled with onshore hydrogen production.

Scenario 3 – Commercial scale offshore wind farm coupled with offshore hydrogen production.

Figure 4.1: Cost Model Scenarios

The cost model allows most of the inputs to these three base scenarios to be modified, enabling inspection of a wide range of possible configurations of wind farm technology (fixed or floating), hydrogen generation and transport. The model will be handed over to the project consortium as a project deliverable. However, this section of the report only presents and discusses the results for the three agreed baseline scenarios. The full characteristics of these are identified below, after a description of the cost modelling methodology.

4.2.1 Methodology of Cost Model Building

The cost model is a Microsoft Excel spreadsheet, with the calculation broken down into CAPEX, OPEX, hydrogen generation, and transport costs. A high-level view of the hydrogen cost modelling methodology is outlined in the diagram below in Figure 4.2.

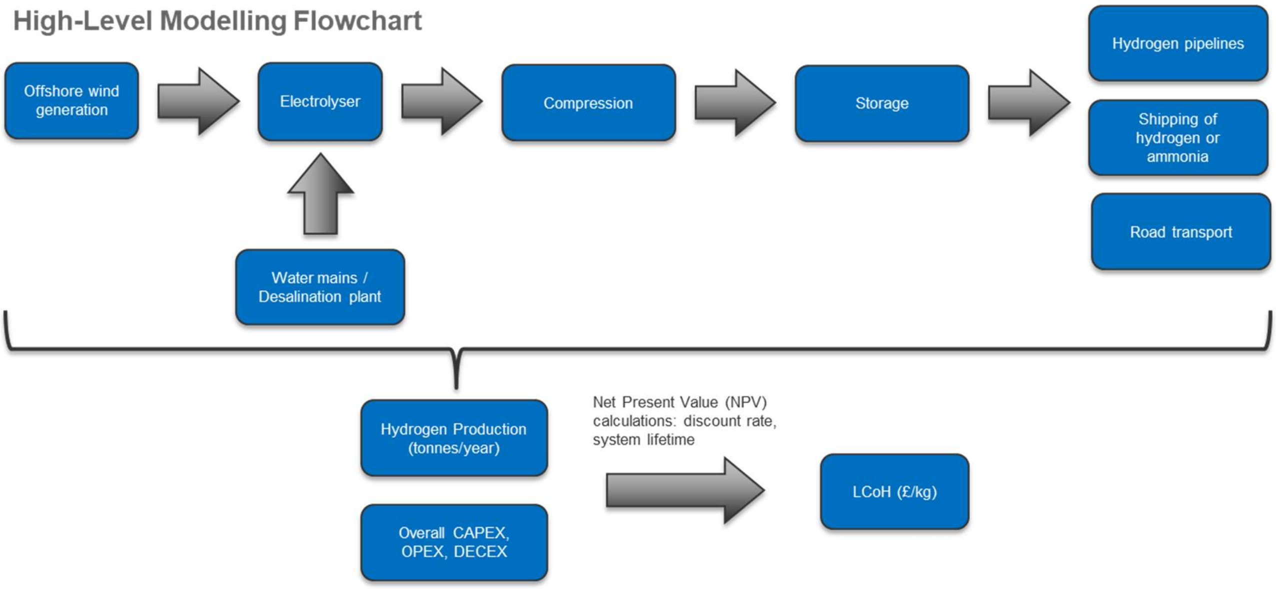


Figure 4.2: LCoH modelling methodology

As the primary focus of the model is to differentiate between hydrogen generation scenarios, the offshore wind farm interface has been purposefully left simple. CAPEX and OPEX values in £/MWh are assumed for each scenario to compute the total costs of the wind farm. The model offers a choice between floating and fixed offshore wind, reflected in the £/MWh value selected. The annual electricity generation from the wind farm is defined by simply multiplying the total wind farm capacity by an average annual capacity factor. CAPEX and OPEX values were taken from Xodus' internal offshore wind LCOE modelling tool.

For the purposes of this cost model and as agreed with study partners during the framing of model scenarios, PEM electrolysers are assumed for hydrogen production. It is recognised that there are several competing electrolyser technologies, and likely to be further emerging new technologies during the period of energy transition considered in this report. The model allows the user to select whether the electrolyser location is offshore or onshore. Hydrogen production in tonnes/year is computed from the electrolyser capacity and utilisation rate. Power for the balance of plant is assumed to come from the offshore wind farm, and this is taken into count when computing the amount of hydrogen produced. Balance of plant includes compression for all scenarios, and desalination for scenarios where the electrolyser is placed offshore. If the electrolyser is placed onshore, Scottish water mains is used as a default for the electrolyser feedwater.

OPEX costs for balance of plant are taken as a percentage of the equipment CAPEX. For the electrolyser, stack replacement after a set number of operating hours is built into the OPEX costs. If balance of plant equipment design life is set as shorter than the project duration, then equipment replacement costs are also taken into account. Decommissioning costs are added for the last year of operation.

Hydrogen transport costs are divided between offshore and onshore delivery costs. In cases where the electrolyser is located offshore, hydrogen offtake can be selected to occur via a subsea hydrogen pipeline or vessels to an onshore location, from where further delivery via gaseous trucking or direct use can be selected. For the largest commercial scale scenario, export over long distances as ammonia or in an additional export pipeline is also included as an option in the delivery costs. An option is also included for onshore buffer storage.

If ‘no storage’ is selected, it is assumed that the product hydrogen is fed directly into the gas grid or used onsite.

Predicted technological learning curves were derived from data taken from research publications to account for increased stack lifetime, reduction in electrolyser CAPEX and reduction in stack replacement cost with time. The model also includes an economies of scale factor accounting for the reduction in unit cost with each additional unit. This factor is applied to electrolyser procurement costs.

The scenarios have not been designed for specific locations, and the distance to shore is theoretical, defined based on the type of project in question. For example, the pilot project is likely to be close to shore, whereas a large commercial scale wind farm generating hydrogen offshore will be situated much further from the coast.

In the final step of the calculation, the NPV of the CAPEX, OPEX, transport costs and hydrogen produced are computed over the lifetime of the wind farm, using a 5% discount rate, to define the LCoH. It is important to note that the model was not intended as a full financial model, but as a comparison between three generation scenarios and for understanding the key cost drivers of green hydrogen.

4.2.2 Cost Model Scenarios and Assumptions

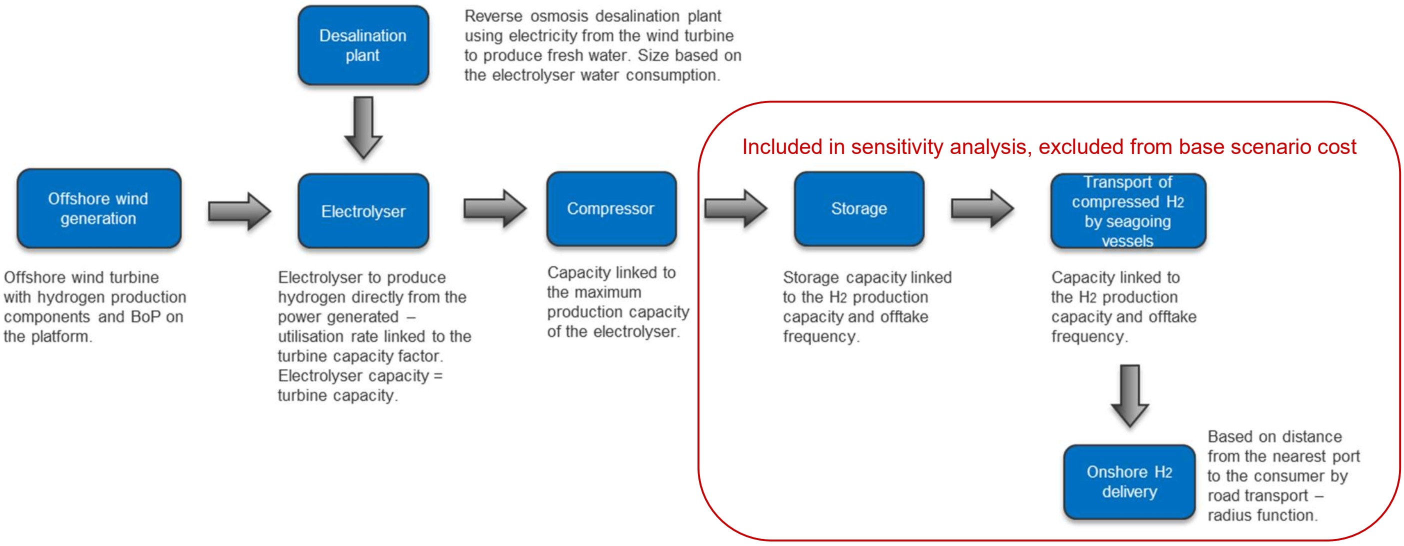
The three model scenarios and relevant assumptions are detailed below.

4.2.2.1 Scenario 1: Pilot Project

Scenario 1 assumes a single turbine, with an electrolyser and desalination unit built onto the same turbine foundation. The hydrogen produced offshore is stored until it is offloaded onto a transport vessel in gaseous form. No onshore storage or further delivery is included, with the assumption that the product hydrogen will be used at the vessel arrival port. Because hydrogen is produced offshore, no export cable is included. The full inputs for scenario 1 are listed below in Table 4.1The high-level flow chart for Scenario 1 is also shown below.

Table 4.1: Scenario 1 assumptions

Variable	Value	Unit
Turbine capacity	14	MW
Wind farm capacity	14	MW
Number of turbines	1	
Actual project capacity	14	MW
Distance from the shore	25	km
Wind farm technology	Fixed	
Electrolyser location	Offshore	
End of construction year	2025	
Project design life	30	years
Fresh water supply	Desalination	
Transport type	Vessel	
Onshore hydrogen storage	No storage	
Onshore hydrogen delivery	No delivery	
Discount rate	5%	
Electrolyser size	494	MW



Reverse osmosis desalination plant using electricity from the wind turbine to produce fresh water. Size based on the electrolyser water consumption.

Offshore wind turbine with hydrogen production components and BoP on the platform.

Electrolyser to produce hydrogen directly from the power generated – utilisation rate linked to the turbine capacity factor. Electrolyser capacity = turbine capacity.

Capacity linked to the maximum production capacity of the electrolyser.

Storage capacity linked to the H_2 production capacity and offtake frequency.

Capacity linked to the H_2 production capacity and offtake frequency.

Based on distance from the nearest port to the consumer by road transport – radius function.

Figure 4.3: Scenario 1 model assumptions

4.2.2.2 Scenario 2: Grid connected wind farm with partial hydrogen generation onshore

Scenario 2 is hydrogen generation onshore from a commercial scale (500MW) fixed offshore wind farm. An export cable runs from site to an onshore electrolyser, sized to match the capacity of the wind farm. For the baseline model results presented here, the wind farm is not grid connected and no network charges are included. However the model enables the user to inspect grid connected scenarios where network charges are taken into account. In such a scenario, the export cable and other transmission infrastructure are sold to the offshore transmission owner (OFTO) at the end of construction. As the model is not location dependent, TNUoS and BSUoS charges have been averaged across the Scottish regions. A 3% economies of scale rate per unit has been applied to the electrolyser procurement costs. Table 4.2 and Figure 4.4 below outline the assumptions for Scenario 2.

Table 4.2: Scenario 2 assumptions

Variable	Value	Unit
Turbine capacity	14	MW
Wind farm capacity	500	MW
Number of turbines	36	
Actual project capacity	504	MW
Distance from the shore	50	km
Wind farm technology	Fixed	
Electrolyser capacity	494	MW
End of construction year	2028	
Project design life	30	years
Fresh water supply	Water mains	
Transport type	Export cable	
Onshore hydrogen storage	No storage	
Onshore hydrogen delivery	No delivery	
Learning rate	10%	
Economies of scale	3%	
Discount rate	5%	

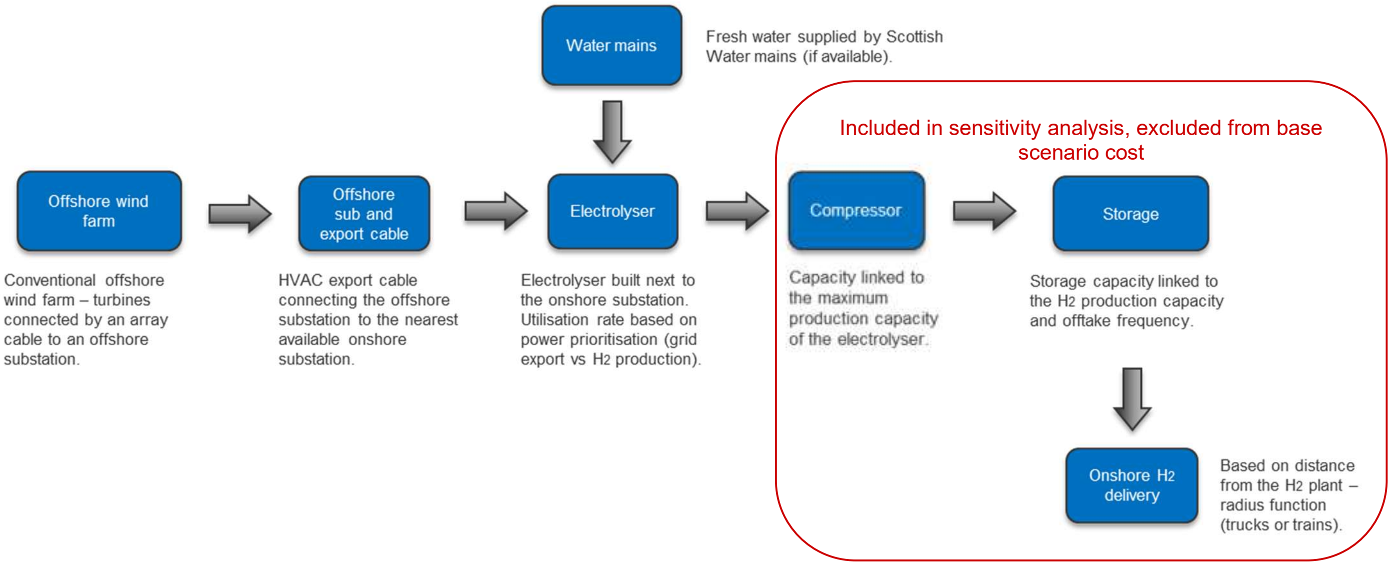


Figure 4.4: Scenario 2 model assumptions

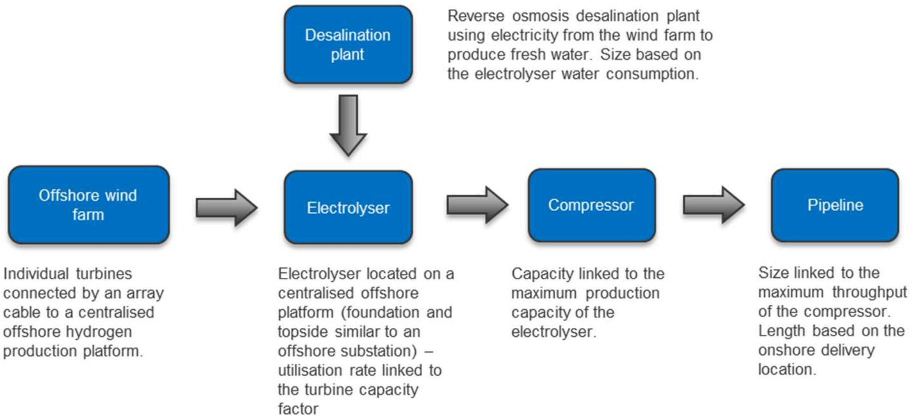
4.2.2.3 Scenario 3: Hydrogen generation offshore from a commercial scale wind farm

Scenario 3 is a large commercial scale offshore wind farm, purpose built for hydrogen generation. The wind farm is not grid connected, and all the energy generated is used for hydrogen production. The electrolysers are located offshore, and the hydrogen is transported to an onshore facility using a subsea pipeline. No further storage or export is included in the baseline scenario.

A 10% learning rate has been applied to stack degradation, and a 3% economies of scale rate per unit has been applied to the electrolyser procurement costs. Table 4.3 and Figure 4.5 outline the assumptions for scenario 3.

Table 4.3: Scenario 3 assumptions

Variable	Value	Unit
Turbine capacity	14	MW
Wind farm capacity	1000	MW
Number of turbines	72	
Actual project capacity	1008	MW
Distance from the shore	100	km
Wind farm technology	Fixed	
End of construction year	2032	
Project design life	30	years
Fresh water supply	Desalination	
Transport type	Pipeline	
Onshore hydrogen delivery	No delivery	
Export delivery distance (Scotland to Europe)	No export in baseline scenario	km
Export delivery type	No export in baseline scenario	
Onshore hydrogen storage	No storage	
Learning rate	10%	
Economies of scale	3%	
Discount rate	5%	
Electrolyser size	1008	MW



Reverse osmosis desalination plant using electricity from the wind farm to produce fresh water. Size based on the electrolyser water consumption.

Individual turbines connected by an array cable to a centralised offshore hydrogen production platform.

Electrolyser located on a centralised offshore platform (foundation and topside similar to an offshore substation) – utilisation rate linked to the turbine capacity factor

Capacity linked to the maximum production capacity of the electrolyser.

Size linked to the maximum throughput of the compressor. Length based on the onshore delivery location.

Figure 4.5: Scenario 3 model assumptions

4.2.2.4 Model assumptions

The values for the key input parameters for all three scenarios are listed in Table 4.4 and Table 4.5

The full list of references for each of the values used is available as part of the Excel model.

Table 4.4: CAPEX assumptions for all scenarios

Variable	Unit	Scenario 1	Scenario 2	Scenario 3
Offshore wind CAPEX (excl. export and array cables) - Fixed	£/MW	2,726,300	2,528,600	2,190,000
Export cable CAPEX	£/m	-	1,000	-
Pipeline to Shore CAPEX	£/m	-	-	650
Project DEVEX	% CAPEX	5	5	5
Array cable CAPEX	£/m	Not included	580	580
Electrolyser CAPEX	£/MW	568,749	484,704	391,638
Compressor CAPEX	£/(tonne/day)	240,000	240,000	240,000

Table 4.5: OPEX assumptions for all scenarios

Variable	Unit	Scenario 1	Scenario 2	Scenario 3
Offshore wind OPEX/year - Fixed	£/MW/year	69984	69984	69984
Offshore wind DECEX	£/MW	330,000	330,000	330,000
Hydrogen DECEX	% CAPEX	2%	2%	2%
Electrolyser OPEX	% CAPEX/year	2%	2%	2%
Lifetime of stack	Hours of operation	50,238	60,667	80,238
Cost of stack replacement	£/MW	175,647	141,758	106,518
Desalination OPEX	£/m^3	1.6	-	1.6
Desalination lifetime	years	30	-	30
Scottish Water charge	£/m^3	-	0.89	-
Compressor OPEX	% CAPEX	6%	6%	6%
Compressor lifetime	years	30	30	30
Pipeline OPEX	£/year	-	-	140,000

4.2.3 Scenario Results

The results for the three base scenarios are presented below in Table 4.6. The breakdown of the lifetime costs for each of the scenarios is also shown graphically in Figures 4.6 to 4.8.

Table 4.6: LCoH model results for base scenarios

Result	Unit	Scenario 1	Scenario 2	Scenario 3
LCOH	£/kg	6.24	2.91	2.26
Total CAPEX (NPV)	£m	46	1,168	1,699
Total lifetime OPEX (NPV)	£m	19	144	248
Average hydrogen production	tonnes/day	3	119	276

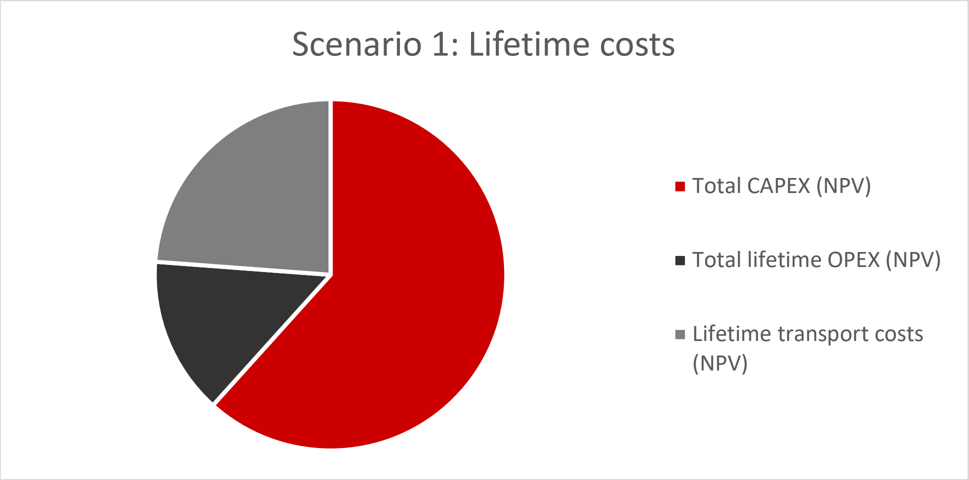


Figure 4.6: Scenario 1 lifetime costs

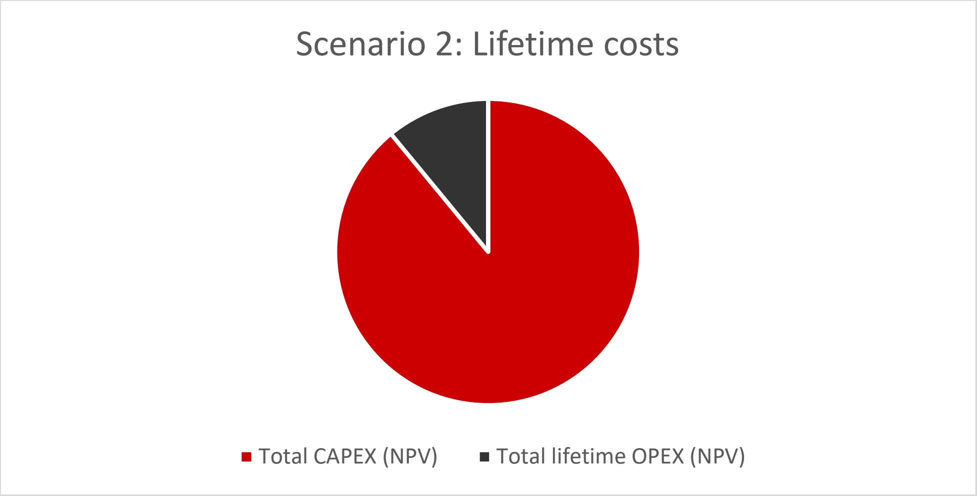


Figure 4.7: Scenario 2 lifetime costs

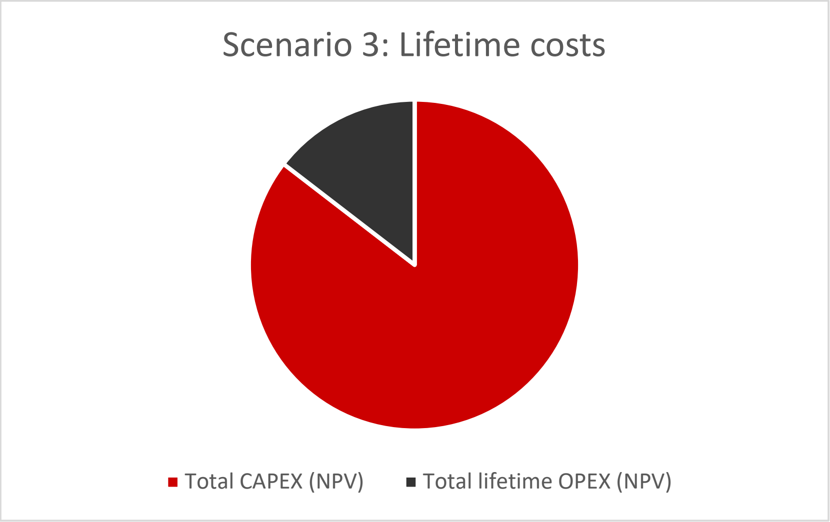


Figure 4.8: Scenario 3 lifetime costs

Scenario 1 LCoH is the highest of the three scenarios at £6.24/kg. This is due to the small capacity of the project. Since the electrolyser is located offshore, vessel transport of produced hydrogen also increases the LCoH. Since the construction of the project occurs in 2025, the electrolyser CAPEX costs are also expected to be significantly higher per MW than for Scenarios 2 and 3. Similarly, the stack lifetime and replacement costs are higher for scenario 1 due to the early timeline. Due to the single unit, no economies of scale or technological learning was applied to Scenario 1, further increasing the LCoH.

The LCoH is for Scenario 3 is the lowest of the three at £2.26/kg. Scenario 2 has an LCoH similar to scenario 2, at £2.91/kg. Scenario 3 LCoH is lower due to the following reasons:

- Offshore electrolyser: Pipeline CAPEX is lower than export cable CAPEX;
- Later delivery year: 2032 compared to 2028; and
- Export cable losses: greater hydrogen production due to no export cable losses;

4.2.4 Sensitivity Analysis

A sensitivity analysis was completed on the LCoH model to identify the key cost drivers for each of the scenarios. The three scenarios presented above are only examples of how the model can be used. In the sensitivity analysis, the model input parameters were modified to their limits for each of the scenarios. Only a single parameter was modified from the original base scenario and the effect on the LCoH recorded. The results of the sensitivity analysis are detailed in Table 4.7 to 4.9.

Table 4.7: Sensitivity Results for Scenario 1

Input variable	Base scenario	Sensitivity analysis	Effect of LCoH	New LCoH (£/kg)
Baseline LCoH				6.24
Turbine foundation	Fixed	Floating	+29%	8.07
Windfarm CAPEX estimate (fixed)	Conservative	Ambitious	-12%	5.51
Electrolyser location	Offshore	Onshore	-13%	5.43
Project design life	30 years	15 years	+24%	7.74
Onshore storage & delivery (gaseous trucking)	No	Yes	+21%	7.56
Discount rate	5%	10%	+33%	8.27
Discount rate	5%	2.5%	-13%	5.43

Table 4.8: Sensitivity Results for Scenario 2

Input variable	Base scenario	Sensitivity analysis	Effect of LCoH	New LCoH (£/kg)
Baseline LCoH				2.91
Distance from shore	50km	100km	+3%	3.00
Distance from shore	50km	25km	-1%	2.87
Windfarm CAPEX estimate (fixed)	Conservative	Ambitious	-26%	2.14
End year of construction	2028	2032	-22%	2.26
Water supply	Mains	Desalination	+1%	2.93
Onshore storage & delivery (gaseous trucking)	No	Yes	+58%	4.60
Discount rate	5%	10%	+63%	4.76
Discount rate	5%	2.5%	-24%	2.20
Turbine foundation	Fixed	Floating	+70%	4.94
Electrolyser CAPEX	485,000	+25%	+4%	3.02
Electrolyser CAPEX	485,000	-25%	-4%	2.80
Electrolyser size	494MW	400MW	+19%	3.47

Table 4.9: Sensitivity Results for Scenario 3

Input variable	Base scenario	Sensitivity analysis	Effect of LCoH	New LCoH (£/kg)
Baseline LCoH				2.26
Turbine foundation	Fixed	Floating	+67%	3.77
Windfarm CAPEX estimate (fixed)	Conservative	Ambitious	-23%	1.74
Distance to shore	100km	200km	+2%	2.31
Distance to shore	100km	50km	-1%	2.24
Export to Europe	None	Pipeline	+10%	2.49
Export to Europe	None	Ammonia	+45%	3.27
Onshore storage & delivery (gaseous trucking)	No	Yes	+65%	3.72
Discount rate	5%	10%	+62%	3.66
Discount rate	5%	2.5%	-24%	1.72

The sensitivity analysis shows that the LCoH is highly dependent on the following:

- Foundation type (floating vs fixed);
- Wind farm CAPEX estimate (conservative vs ambitious);
- Inclusion of transport and storage costs; and
- Discount rate.

The following factors have relatively little effect of LCoH:

- Fresh water supply (Scottish water mains vs. desalination); and
- Distance to shore.

The LCoH is significantly affected by the transport and export costs included. Table 4.10 below shows the assumptions used in defining the transport costs in the model. To provide a fair comparison, none of the baseline scenarios include any transport costs. However, when examining the financial feasibility of the scenarios, it is important to consider the cost implications related to storage and delivery. The sensitivity analysis for Scenarios 2 and 3 shows that the inclusion of storage and delivery as gaseous trucking increases the LCoH significantly, by more than 60%. For Scenario 3, export to Europe as Ammonia increases the LCoH by 45%, whereas export via a pipeline is significantly more cost effective, at only a 10% increase to the baseline cost.

Table 4.10: Transport cost assumptions for all scenarios

Variable	Unit	
Vessels	£/day	48,000
Gaseous trucking	£/kg	0.8
Export Pipeline CAPEX	£/m	650
Transformation from H2 to NH3	£/kg	0.75
Reconversion from NH3 to H2	£/kg	0.09
Ammonia export	£/kg	0.17

The model includes two input values for fixed and floating offshore wind CAPEX costs; a conservative estimate and an ambitious estimate. The conservative estimate is based on the Xodus internal CAPEX tool and is considered relevant for 2025-2032 (cost reduction curve of 15% between 2028 and 2032). The ambitious estimate aligns with the inputs of the *ORE Catapult in their OSW-H2: Solving the integration challenge* report and can be used to model LCoH for scenarios where significant cost reductions in offshore wind costs are anticipated, such as long-term ambitions. The sensitivity analysis shows that ambitious wind farm CAPEX figure lowers the LCoH by approximately 25%.

The key output of the sensitivity analysis is that the LCoH is highly dependent on how the baseline scenarios are defined and how much of the post-processing and delivery are included. Overall, the results of the three baseline scenarios were as anticipated and align with other cost-models in the public domain. For example. Scenario 3 is similar to the scenarios explored by *ORE Catapult in their OSW-H2: Solving the integration challenge* report. For 2030, OREC predict a £2.2/kg LCoH for a fixed 1.2GW offshore wind farm with offshore generation. This is very close to the Scenario 3 baseline LCoH of £2.26/kg.

4.2.5 Summary

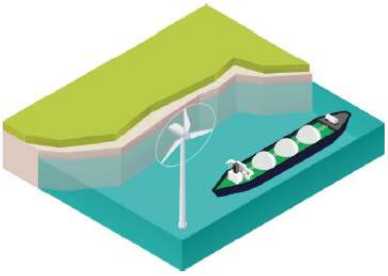
Levelised cost of hydrogen (LCoH) has been estimated for three base case production scenarios:

> Scenario 1: Small-scale pilot project for green hydrogen production from offshore wind;

> Scenario 2: Commercial scale offshore wind farm coupled with onshore hydrogen production;

> Scenario 3: Commercial scale offshore wind farm coupled with offshore hydrogen production.

Table 4.11: Cost Model Summary



Scenario 1 – Small-scale pilot project for green hydrogen production from offshore wind.

Scenario 2 – Commercial scale offshore wind farm coupled with onshore hydrogen production.

Scenario 3 – Commercial scale offshore wind farm coupled with offshore hydrogen production.

Result	Unit	Scenario 1	Scenario 2	Scenario 3
Year		2025	2028	2032
Wind Farm Capacity	MW	14	500	1000
Hydrogen Production	Te/day	3	119	276
LCoH	£/kg	6.2	2.9	2.3

> As expected, the results of the modelling show the cost of hydrogen production decreasing with reducing technology cost and increased scale. Xodus' analysis supports a long term outlook of LCoH falling towards £2/kg for fixed bottom offshore wind turbines.

> Floating wind and any additional costs for transportation significantly increase the LCoH. The cost of hydrogen at the point of use must therefore take these logistics components into account on a case by case basis.

> Desalination cost and distance to shore do not significantly influence LCoH.

4.3 Hydrogen Policy Analysis

The possibility of using hydrogen to decarbonise various energy-intensive sectors has been considered within wider energy policies in many countries to date. However, dedicated national hydrogen strategies are starting to emerge only in the past two years, with one exception, Japan, which has been a hydrogen leading nation for decades. Other countries, including the UK, Germany or Australia, are now following the suit and recognising hydrogen as a viable option to meet their net-zero targets. Australia and Germany have now published their national hydrogen strategies, EU Green Deal recognises hydrogen sector as a key player, and the Scottish and the UK Governments are also increasingly considering the next steps to support hydrogen supply and use from the late 2020s onwards. This section summarises the most recent developments in the hydrogen policy arena to support Scotland's 2045 net-zero target and what may be required to replace fossil fuels with green hydrogen instead.

4.3.1 EU Hydrogen Policy Landscape

The EU has pursued its long-term decarbonisation strategy which includes a hydrogen pathway to achieve the net-zero target. The EU has committed to support hydrogen production from renewable sources, and to set up the Hydrogen Energy Network as a platform to connect EU member states and encourage further discussion about the benefits and barriers associated with hydrogen economy. This has emerged from the Linz Declaration Hydrogen Initiative, which has been signed by 28 European countries, and 100 businesses, organisations and institutions to accelerate the uptake of hydrogen technology in the EU (IEA, 2019).

The European Commission has been continuously supporting innovative hydrogen projects through various initiatives, the largest being the Fuel Cell and Hydrogen Join Undertaking (FCH JU) under the Horizon 2020 framework (FCH JU, 2020). FCH JU is an EU-led initiative that supports research, technological development and demonstration activities within the hydrogen sector. FCH JU facilitates a total funding budget of £1.2 billion between 2014 and 2020 (FCH JU, 2020). The FCH JU has already funded 246 hydrogen demonstration projects in Europe, with electrolysers receiving around 80% of the funding (EURACTIV, 2019). The last Call for Proposals included 24 topics and has a budget of £83 million. The FCH JU led to the creation of the Mission Innovation, Renewable and Clean Hydrogen Innovation Challenge, which aims to accelerate the development of a global hydrogen market by identifying and overcoming key technology barriers. The group includes 15 countries that are the most active in hydrogen economy – including the UK and other non-EU members such as Japan or Australia.

4.3.1.1 EU Hydrogen Strategy

A hydrogen strategy for a climate neutral Europe (European Commission, 2020) is a clear example of EU's dedication to support a wide deployment of hydrogen technologies across Europe and beyond. The strategy is primarily focused on three milestones between 2020 and 2045. From 2020-2024, the goal is to deploy at least 6GW of green hydrogen production facilities, with the capacity of producing 1 million tonnes of green hydrogen per year. In a period of 2025-2030 the Commission expects to see a significant increase of green hydrogen production from 6GW to 40GW to produce 10 million tonnes of hydrogen annually. In 2045, the green hydrogen technology is expected to be deployed at a large scale to decarbonise all *hard-to-abate* sectors in the EU.

The Commission is convinced that the long-term green hydrogen production will be underpinned by wind and solar generation, which are already the cheapest sources required for electrolysis, and these costs are likely to fall even further. In the in the short and medium terms, the Commission acknowledges that other forms of low-carbon hydrogen will also be required to create a viable, large-scale market.

The development of appropriate certification and lifecycle assessment will be critical to ensure that supplied hydrogen comes from low-carbon sources. The Commission has committed to introduce a comprehensive terminology and certification, to deliver this commitment. The scheme will be focused on life-cycle carbon emissions, including all components and processes required to produce and deliver green hydrogen to the end-user. This will be underpinned by existing EU legislation and correspond with the EU taxonomy for sustainable investments. Complying with this certification scheme will be critical for Scotland's potential green hydrogen export to the EU.

The EU hydrogen strategy highlights that the rapid increase of green hydrogen production will be crucial to recover from the COVID-19 crisis. The European Commission recover plan *'Next Generation EU'* states that investing into hydrogen technologies is a priority to ensure that EU adapts to sustainable economic growth and becomes the leading region of hydrogen development by creating long-term, resilient jobs. The EU Green Deal also considers hydrogen to be an important part of Europe's energy future, including innovative projects such as zero-carbon steel making.

4.3.1.2 Europe's Hydrogen Leading Countries

Two of the most active European countries that drive hydrogen technology innovation and pilot project deployment are the Netherlands and Germany. Both countries agreed on an official hydrogen cooperation in October 2019, following the Eur 20 million EU funding from FCH JU for the Hydrogen Valley project for Northern Netherlands (Hyer, 2019). The aim of this mutual collaboration is to develop a dedicated European hydrogen directive, initially led by the Netherlands and Germany together with their northwest Europe partners (Austria, Belgium, France, Luxemburg and Switzerland) (Fuel Cell Works, 2019).

The German Government has already been supporting hydrogen-related projects through their National Innovation Programme for Hydrogen and Fuel Cell Technologies. The current 10-year programme (2016-2026) includes £1.25 billion funding from the German Government and additional a £1.8 billion funding from private investors. The programme is primarily focused on publicly accessible hydrogen refuelling stations and hydrogen fuel cell modes of transport (IEA, 2019). The German Government also funded the world's first hydrogen-powered train.

In June 2020, Germany published its first dedicated hydrogen strategy: *The National Hydrogen Strategy* (German Federal Government, 2020). The strategy aims to develop German's hydrogen sector, whilst highlighting the key opportunities and barriers related to hydrogen supply and end-use. Considering the population density and economy based on industrial processes, it is likely that Germany will require hydrogen import from other European countries to decarbonise its energy-intensive sectors. This is where Scotland-Germany partnership could become a viable solution.

The Strategy highlights that strong international partnerships will be critical to deliver the hydrogen market scale required. Germany is particularly interested in creating new energy partnerships with countries that already have active development cooperation with and potential energy exporters with significant renewable energy resources to produce green hydrogen. Scotland is therefore an ideal candidate to meet both of these requirements. Producing green hydrogen from wind energy and exporting it to Germany by subsea pipelines or ships could become an important trade relationship between the two countries. The list of selected countries for potential cooperation will be produced during the German EU Council Presidency (German Federal Government, 2020).

Pipelines and ammonia are mentioned in the Strategy as the key options for long-distance hydrogen transport based on the existing infrastructure and capabilities. Liquid hydrogen or LOHCs could also become increasingly important. However, these technologies are less mature compared to the former.

The Strategy also calls for appropriate standardisations and certification, similarly to the EU Hydrogen Strategy. Successful establishment of the international hydrogen market will be reliable upon proof of origin for power used for electrolysis, as well as sophisticated standards for high-quality hydrogen infrastructure. Therefore, the German Federal Government has committed to join up with other countries to create universal standards and codes within the international hydrogen market.

4.3.2 Other Hydrogen Leading Regions

Hydrogen technology innovation in the Asia-Pacific (APAC) region is currently driven predominantly by Japan, Australia, China and South Korea. Some countries have published dedicated national hydrogen strategies (Australia in November 2019 (COAG, 2019) and Japan in December 2017 (Japanese Government, 2017)), which include estimations of their future hydrogen demand and supply and outline potential paths how to get there. While Japan is already a global leader in hydrogen technology with operational strategy to import hydrogen to meet their growing demand, the Government of Australia has officially committed to hydrogen technology in 2019 through its dedicated national strategy, mainly focused on the production side.

Japan is planning to import around 12 TWh by 2030, as well as investing heavily in research and investments into international hydrogen supply chains and end-use technology (Committee on Climate Change, 2018). Australia has several projects in the pipeline to export hydrogen to Japan. This cooperation is a similar relationship to Scotland and continental Europe, where Scotland could export green hydrogen from its abundant renewable energy resources to support decarbonisation efforts in densely populated countries with less abundant renewable energy resources.

The idea of exporting energy from regions with abundant, low-cost resources to locations with higher demand is not new. Importing renewable electricity from northern Africa to Europe has been considered in the past. Although there are several complex non-technical issues that are not in a favour of this development, there are also some technical obstacles to overcome, such as the prohibitive cost of power transmission lines from Africa to Europe. Hydrogen, on the other hand, can be used as an energy vector to overcome long-distances in pipelines, ships, or trucks, whether gaseous, liquified, or stored in other forms, which costs much less than power transmission cables (FCH JU, 2019). This is the main reason why sparsely populated Australia with abundant solar, wind and coal resources is interested in supplying Japan with hydrogen carried on board of ships.

4.3.3 Scotland’s Hydrogen Policy Landscape

Opportunities associated with a wide deployment of hydrogen technology in Scotland are thoroughly explored in the Scottish Government’s most recent energy-related policy papers. Both the Scottish Energy Strategy published in 2017 and the Electricity and Gas Network Vision for 2030 published in 2019 focus on the whole-systems approach, which aligns well with hydrogen production and use. The Scottish Government’s commitment to become a leading hydrogen nation has already paid off with Scotland being the world’s first to produce hydrogen from tidal energy (Surf’n’Turf), and combining anaerobic digestion, combined heat and power and electrolysis to produce and utilise hydrogen and oxygen as part of the OHLEH project. Furthermore, Scotland is now planning to deploy the first seagoing renewable-powered hydrogen ferry (HySeas III), develop the first offshore hydrogen production from floating wind (Dolphyn) and build the first large-scale offshore CCS plant to produce hydrogen (Acorn Hydrogen). All these projects were financially supported by the Scottish Government, UK Government, or the EU.

The Vision for 2030 paper states that Scotland’s gas network will remain a crucial component of the national infrastructure which will keep delivering affordable energy to heat homes and businesses. The policy, regulatory and technical developments will have to be designed in a way that will allow natural and low carbon gas to be blended in the networks, including a contribution from hydrogen. The Scottish Government has committed to understand the feasibility and associated costs of repurposing the gas networks to accommodate 100% hydrogen supply (Scottish Government, 2019). By 2030, the Scottish Government has committed to implement strategic decisions about the long-term role of the gas networks which is likely to deliver desired certainty around the deployment of hydrogen systems in Scotland.

The Scottish Government is planning to build upon their previous support for hydrogen projects. They are currently preparing an interactive mapping tool which will display current hydrogen activity in Scotland and showcase specific hydrogen production and use opportunities on a region by region basis (Scottish Government, 2019). The Scottish Government has also committed to continue working with external stakeholders to advance hydrogen energy and transport initiatives, accompanied by clear analysis and policy statements associated with the role of hydrogen in Scotland’s future energy system. The most important developments in Scotland that are on the horizon are as follows (CMS, 2020);

- Hydrogen Accelerator Programme
- Hydrogen Assessment Project
- Action Plan for Development of Hydrogen Economy

- Hydrogen Fuel Cell Train Pilot Projects

4.3.4 Potential Hydrogen Policy and Market-Driven Incentives

Green hydrogen projects in Scotland, as well as worldwide, have been funded predominantly on a project-by-project basis to climb the Technology Readiness Level (TRL) ladder. However, consistent and long-term support schemes will be required for the green hydrogen technology to enter the large-scale deployment stage. These schemes could use lessons learned from the renewable power generation sector, either policy-led (such as Renewable Obligation or Contracts for Difference), or market-based (such as Power Purchase Agreements). These schemes will be critical for Scotland to meet its net-zero target by 2045 if hydrogen is to play an important role in the future energy mix. This section discusses what schemes could be adopted to support green hydrogen development in Scotland.

4.3.4.1 Renewable Transport Fuel Obligation

Renewable Transport Fuel Obligation (RFTO) is the UK Government incentive scheme to decrease the carbon footprint within the transport sector by supporting the use of biofuels (UK Gov, 2019). RFTO is a requirement for transport fuel suppliers to ensure that a certain proportion of their fuel sold comes from biofuels. This obligation-based scheme is a similar one to the electricity generation sector, which boosted the renewable power generation capacity through Renewable Obligation Certificates (ROCs).

Using green hydrogen within the transport sector is likely to be one of the most cost-competitive sectors, based on the results in Section 3. Hydrogen is already categorised under the RTFO as a development fuel, although it does not apply to grid electricity electrolysis nor states any percentage of transport fuels to come from green hydrogen. Setting a certain percentage to come from electrolysis rather than fossil fuels (with the percentage increasing gradually every year) could significantly increase the use of green hydrogen within the transport sector.

Since electric vehicles will inevitably play an important role in the decarbonisation efforts of the transport sector (particularly light-duty vehicles), the RFTO should ensure that it supports low-carbon technologies to replace petrol and diesel, and not discourage electrification. This scheme could unlock the use of hydrogen in the transport sector in a consistent and predictable way, without requiring funding support based on a project-by-project basis.

4.3.4.2 Low Carbon Obligation

Low Carbon Obligation (LCO) could follow a similar method to RFTO but focusing on the heat sector instead of transport. The heat sector is the most promising sector in terms of hydrogen demand potential but equally the least cost-competitive sector compared to the fossil fuel replaced. Therefore, the LCO scheme would have to be designed in a way to ensure that heating bills do not significantly increase by replacing natural gas with more expensive green hydrogen.

Scotland is ideally located for hydrogen blending, due to the significant offshore wind resources and the presence of St Fergus gas terminal. Therefore, LCOs focused on low-carbon heating could boost the uptake of green hydrogen technologies in Scotland, whilst helping to decarbonise Scotland’s heat sector by 2045.

4.3.4.3 Hydrogen Purchase Agreements

Hydrogen Purchase Agreement (HPA) could become a market-based solution based on the same principle of the conventional Power Purchase Agreement (PPA). HPA would be created between a green hydrogen producer and a hydrogen end-user by setting a certain sale price (£/kg) and amount used in a given timeframe (e.g. in kg/day). This market-driven solution could help to solve the ‘chicken and egg’ situation between hydrogen supply and demand.

Although HPAs would be market-driven, certain standardisation and rule compliance will be required from the policymakers and regulators, to protect both sides. Purchase Agreements are already common in the renewable power sector, and they can also create a level-playing field in the hydrogen sector, especially if combined with other policy-led mechanisms such as the combination of CfD and PPA in the renewable electricity sector (OFGEM, 2020).

4.3.4.4 Green Electricity CfD Auctions with Electrolysis Option

It might be possible to incentivise increased use of hydrogen and electrolysis through modifications to the existing CfD auction infrastructure currently in place to support low-carbon electricity technologies. Rather than offering a CfD for hydrogen technologies directly, a stipulation could be introduced that zero-carbon asset operators would only receive payment for electricity delivered either directly to the grid or into an electrolyser (with electrolysis only being an option when the grid is saturated). This would allow the asset operator to produce hydrogen at a very competitive price should they face curtailment.

Further cost reductions could be encouraged should feed-in priorities be made tradeable. Investment in electrolysers would only be attractive to asset-owners who are likely to face curtailment. Should one developer be based in a location with strong grid connection but poor hydrogen delivery options, and another in a location with strong hydrogen delivery options but a poor grid connection, they could trade feed-in priorities such that the former is able to maximise production to the grid, where the latter produces hydrogen. This would encourage market efficiency.

4.3.4.5 Emission Abatement Potential and Subsidies

To close the gap between hydrogen supply cost and the end-user price in sectors that are unlikely to compete with fossil fuels under current tax regimes, there are two ways to be introduced. The first option is to provide direct subsidy to lower the costs associated with green hydrogen production, storage and delivery to the end user. This would enable the final price of green hydrogen to be equal to the cost of fossil fuels used in the given sector. This could be referred to as *positive* subsidy.

The second option is to penalise carbon emitting sectors by introducing carbon price based on the carbon intensity of each fuel based on the emission abatement potential within each sector.

This section discusses how much hydrogen could be taxed or how much subsidy will be required to replace existing fossil fuels either by positive subsidy or emission penalty.

Hydrogen could replace different types of fossil fuels across various energy sectors, such as road transport, low-grade and industrial heat, chemical feedstock, electricity, ferries or aviation. Each of the sectors use different fuels and technologies with different efficiencies. The carbon intensity of each sector shown in Figure 4.9 identifies sectors that are the most promising to become decarbonised by replacing traditional technologies that use fossil fuels with green hydrogen. These carbon intensity results (also referred to as emission abatement potential) were based on technologies assessed in Section 2.4.

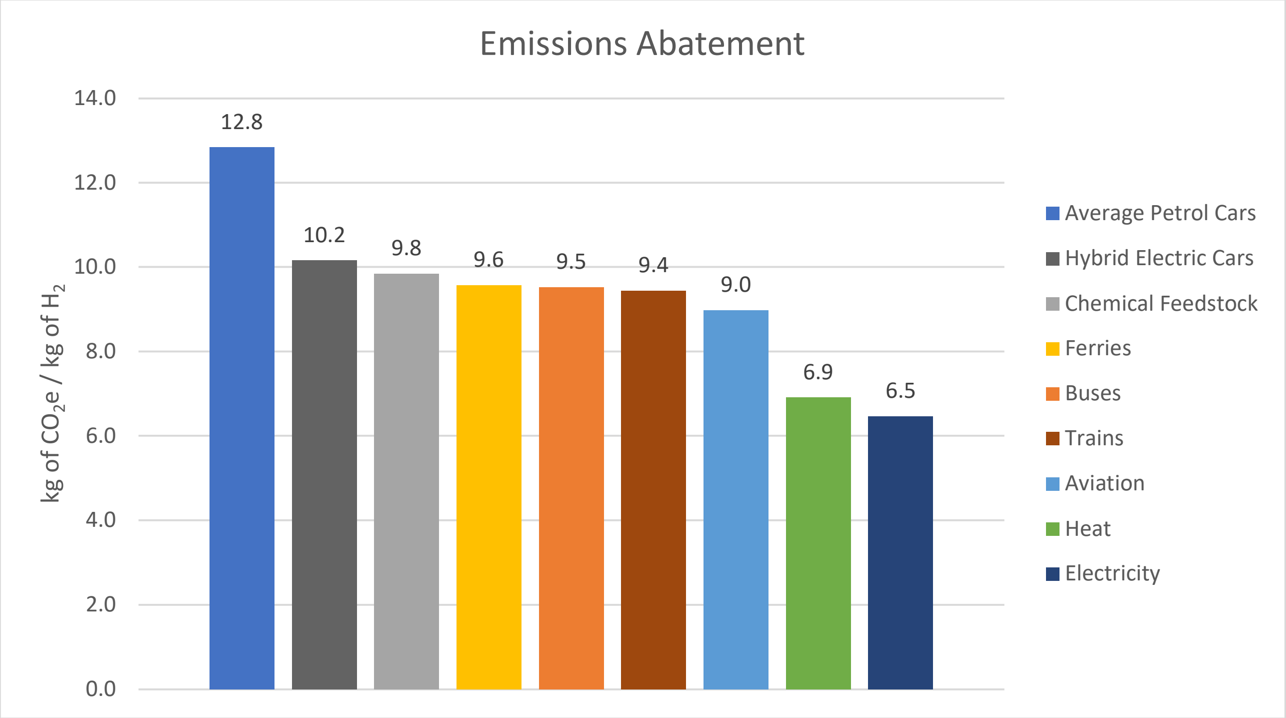


Figure 4.9. Emissions abatement potential (green hydrogen vs fossil fuel technologies)

Similarly to Section 2.4, each sector comparison shown in Figure 4.8 is based on delivering the equivalent service. This can be demonstrated on a road transport example: 0.94 kg of green hydrogen will allow an FCEV to travel 100 km. The same distance will require 5.5 litres of petrol when using an average petrol car. Travelling 100 km in a petrol car would emit 12.8 kg of carbon dioxide equivalent according to the UK Government's Conversion Factors document, which states a figure of 2.2 kg of carbon dioxide equivalent per litre of petrol used (UK Gov, 2019). It should be noted that the emission abatement potential is linked not only to the fuel used (UK Government's Conversion Factors) but also to the efficiency of each technology used across various sectors.

With regards to Conversion Factors, kerosene for aviation and MGO have the highest carbon dioxide equivalent factor per kg of fuel used, followed by petrol and diesel. Natural gas has the lowest emission factor. Conversion factors that were used for the emissions abatement potential calculations are shown in Table 4.11

Table 4.11: Conversion Factors used for the emission abatement potential calculations

Fuel	Unit	kg Co2e
Natural gas	tonnes	2542.04
	cubic metres	2.03053
	kWh	0.18385
Aviation turbine fuel	tonnes	3218.92
	litres	2.29105
	kWh	0.24455
Diesel	tonnes	3088.23
	litres	2.59411
	kWh	0.24462
Petrol	tonnes	2997.5
	litres	2.20904
	kWh	0.23373
Marine fuel oil	tonnes	3159.55
	litres	3.12209
	kWh	0.26298

Regarding efficiency improvements when replacing fossil fuel technology with hydrogen, transport modes running for long durations without frequent start-stop situations run at the optimum regime of the engine, and therefore the engine performance is the closest to the nameplate efficiency. This applies to sectors such as ferries. On the other hand, buses and particularly cars are the most penalized by the start-stop nature of urban traffic, as they waste energy on idling or part load. Therefore, replacing fossil fuel technologies with hydrogen are anticipated to improve the least for ferries, whereas buses and cars are anticipated to improve the most. This is the reason why emission abatement potential per 1 kg of hydrogen used is the highest in cars, even though 1 kg of petrol has lower Conversion Factor compared to other liquid hydrocarbons.

In this analysis, aviation has the lowest emissions abatement potential since the future technology is still unknown, so only LHV of each fuel were compared in Section 2.4 without any efficiency improvements assumed. Therefore, emission abatement potential of aviation shown in Figure 4.8 is only indicative and further analysis will be required to obtain more accurate results

1 kg of green hydrogen can be seen to avoid significantly more emissions when it is used to replace liquified fossil fuels (such as marine gas oil, kerosene, petrol or diesel) compared to natural gas used for heating or back-up electricity generation.

The lower the emissions abatement potential, the more difficult it would be for green hydrogen to compete with fossil fuels if carbon price was introduced. Put another way, the lower the emissions abatement potential, the higher carbon price would be required to level the playing field.

Carbon price required for each sector to level the playing field between fossil fuels and green hydrogen can be calculated as follows;

*Carbon Price (£/tonne of CO2e) = Cost of Hydrogen Supply (£/kg) – Cost Parity per Sector (£/kg) / Emissions Abatement Potential (kg of CO2e / kg of H2) * 1,000*

There are several uncertainties to be addressed before this approach can be applied, with some of them being out with the scope of this study. Firstly, cost of hydrogen supply needs to include not only cost of green hydrogen production from offshore wind (see Section 4.2) but also all the costs associated with delivering this hydrogen to the end-user. For example, in road transport, hydrogen would need to be transported to refuelling stations that require on-site hydrogen storage and dispensers. Secondly, cost parity per sector varies significantly depending on Fuel Duty and VAT applied, and it was out with the scope of this study to analyse potential changes within the HMRC existing tax regime.

To provide a high-level cost comparison of hydrogen supply and cost parity in 2032, Figure 4.10 shows cost parity results within each sector and the range of hydrogen supply cost based on the LCoH model.

The LCoH bottom line of £2.3/kg was based on the baseline results of Scenario 3, which assumed large-scale hydrogen production offshore and delivery to the shore. The upper line added £1.3/kg of hydrogen to the production cost for hydrogen compression, storage and delivery to the end-user in gaseous trucks (see Sensitivity analysis for Scenario 3 in Section 4.2). It should be noted that hydrogen storage on-site at the point of use location (e.g. at the refuelling station) and dispensers were not included in the LCoH values, since the study focused on upstream and midstream only.

It can be anticipated that hydrogen supply costs per kg would be lower for heat and electricity sectors compared to road transport, since hydrogen blended into the existing natural gas network would not require hydrogen tube trailers to be distributed around Scotland, whereas the additional cost of storage and road delivery would be required to supply hydrogen refuelling stations. Figure 4.is intended to provide only a high-level indication of hydrogen cost-competitiveness across various sectors, rather than detailed assessment that would be required to look at each sector in further detail.

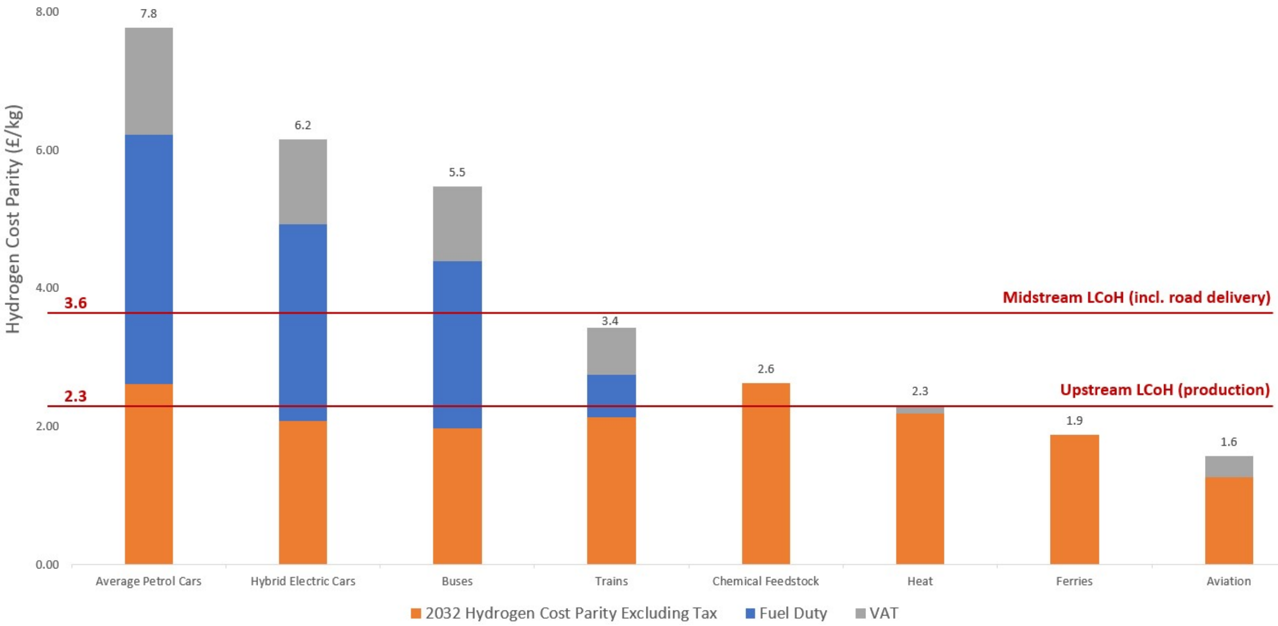


Figure 4.10. Estimated cost of hydrogen supply vs cost parity across various sectors in 2032

This shows that cars and buses are the only sectors where cost parity exceeds hydrogen supply, which means that hydrogen used in these sectors could be taxed with Fuel Duty and VAT (although at lower rates than current regime) and still compete with existing costs of petrol and diesel. This is predominantly due to the fact that Fuel Duty and VAT currently account for two thirds of petrol and diesel cost.

Green hydrogen used to decarbonise trains and chemical feedstock could be cost-competitive with diesel and Grey hydrogen, respectively, only if the delivery cost is below the upper band of midstream LCoH cost, which is unlikely if gaseous trucking is used for hydrogen delivery. Otherwise these sectors will require subsidy to close the supply-demand cost gap.

The cost parity of remaining sectors is either very similar to the cost of hydrogen production (heat), or well below (ferries, aviation) which suggests that subsidies will be required to level the playing field, especially considering that the overall supply cost will be higher than the bottom band that only shows cost of hydrogen production *without* storage, or delivery.

Table 4.12 provides a summary of the cost comparison between hydrogen supply and demand, as well as an indication of carbon price that would be required to decarbonise these sectors. It should be highlighted that the calculations were based on cost parity including Fuel Duty and VAT (e.g. hydrogen to power trains would only be cost-competitive with diesel if it was excluded from Fuel Duty and VAT and there was a carbon price of £19/tonne of carbon dioxide equivalent).

Heat sector results were presented as a wide range since the cost of transmission and distribution of hydrogen in the existing gas network was not assessed within the study, but these costs are likely to be lower than transporting hydrogen in gaseous trucks. Electricity was excluded from the summary table due to the uncertainties around cost parity assumptions. Further work will be required to understand the implications and costs associated with replacing natural gas with hydrogen, especially considering that more than half of Scotland's total energy demand comes from heat (the majority using natural gas).

Table 4.12. Summary of hydrogen cost-competitiveness in 2032 across various sectors

Sector	Cost of Hydrogen Production and Delivery (£/kg of H_2)	Cost Parity Including Fuel Duty and VAT (£/kg of H_2)	Cost Competitive (+) / Subsidy Required (-) (£/kg of H_2)	Difference (%)	Carbon price required (£/tonne of CO_2e)
Average Petrol Cars	3.6	7.8	+4.2	+54%	0
Hybrid Electric Cars	3.6	6.2	+2.6	+41%	0
Buses	3.6	5.5	+1.9	+34%	0
Trains	3.6	3.4	-0.2	-5%	19
Chemical Feedstock	3.6	2.6	-1.0	-37%	99
Heat	2.3 to 3.6	2.3	0 to -1.3	0% to -57%	0 to 188
Ferries	3.6	1.9	-1.7	-91%	180
Aviation	3.6	1.6	-2.0	-129%	226

It should be reiterated that the cost parity projections and the consequential carbon price estimates only considered the cost of fuel (operating costs) and not the total cost of ownership. Therefore, this analysis should be considered as indicative and could be further improved upon by assessing the total cost of ownership rather than considering operating costs only. Further analysis will be required to obtain more accurate results.

4.3.5 Summary

To enable a wide uptake of hydrogen end-use technologies across Scotland, the capital cost for the initial investment in hydrogen technology is likely to require incentives due to the cost disparity between traditional fossil fuelled technology and newer hydrogen technology. Such example can be seen in the light-duty vehicle sector, where the capital cost required to buy a hydrogen car is significantly higher compared to an equivalent petrol vehicle. However, when considering only operating costs associated with the cost of fuel, the analysis concluded that in 2032 green hydrogen used in cars and buses could be taxed (although at a lower rate than current Fuel Duty and VAT) and still be cost-competitive with current fossil fuel prices.

The rest of the sectors will require subsidies to level the playing field with the existing use of fossil fuels. Although a carbon price of around £200/tonne of carbon dioxide equivalent seems like an ambitious number, it is not unrealistic based on the progressively increasing carbon price in other countries, such as Sweden. Sweden currently has one of the highest carbon prices in the world, which is £100 per tonne of CO_2e in 2020 (Swedish Gov, 2020). Sweden's carbon price is likely to keep increasing as it has been since its introduction in 1991.

If Scotland followed a similar concept, it could enable green hydrogen to become cost competitive with most fossil fuel powered technologies by 2032. Based on the Swedish example, Scotland could follow the suit and introduce an ambitious carbon price to level the playing field and allow low carbon technologies to replace polluting fossil fuels and contribute towards the net-zero target by 2045.

5 CONCLUSION - KEY FINDINGS

- Scotland has an abundant offshore wind resource that has the potential to be a vital component in our net zero transition. If used to produce green hydrogen, offshore wind can help abate the emissions of historically challenging sectors such as heating, transport and industry.
- The production of green hydrogen from offshore wind can help overcome Scotland's grid constraints and unlock a massive clean power generation resource, creating a clean fuel for Scottish industry and households and a highly valuable commodity to supply rapidly growing UK and European markets.
- The primary export markets for Scottish green hydrogen are expected to be in Northern Europe (Germany, Netherlands & Belgium). Strong competition to supply these markets is expected to come from green hydrogen produced from solar energy in Southern Europe and North Africa.
- Falling wind and electrolyser costs will enable green hydrogen production to be cost-competitive in the key transport and heat sectors by 2032. Strategic investment in hydrogen transportation and storage is essential to unlocking the economic opportunity for Scotland.
- Xodus' analysis supports a long-term outlook of LCoH falling towards £2/kg, with an estimated reference cost of £2.3 /kg in 2032 for hydrogen delivered to shore.
- Scotland has extensive port and pipeline infrastructure that can be repurposed for hydrogen export to the rest of UK and to Europe. Pipelines from the '90s are optimal for this purpose as they are likely to retain acceptable mechanical integrity and have a metallurgy better suited to hydrogen service. A more detailed assessment of export options should be performed to provide a firm foundation for early commercial green hydrogen projects.
- There is considerable hydrogen supply chain overlap with elements of parallel sectors, most notably, the oil and gas, offshore wind and subsea engineering sectors. Scotland already has a mature hydrocarbon supply chain which is engaged in supporting green hydrogen. However, a steady pipeline of early projects, supported by a clear, financeable route to market, will be needed to secure this supply chain capability through to widescale commercial deployment.
- There are gaps in the Scottish supply chain in the areas of design, manufacture and maintenance of hydrogen production, storage and transportation systems. Support, including apprenticeships, will be needed to develop indigenous skills and capabilities in these areas.
- The development of green hydrogen from offshore wind has the potential to create high value jobs, a significant proportion which are likely to be in remote, rural/coastal communities located close to offshore wind resources. These can serve as an avenue for workers to redeploy and develop skills learned from oil and gas, in line with Just Transition principles.

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