Scottish Hydrogen Assessment

December 2020

Scottish Government
Riaghaltas na h-Alba
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CONTENTS

ACRONYMS, TABLES AND FIGURES

ACRONYMS

ADL	Alexander Dennis Limited
AECC	Aberdeen Exhibition Conference Centre
ATR	Auto Thermal Reforming
Big HIT	Building Innovative Green Hydrogen Island Territories
bn	Billion
CapEx	Capital Expenditure
CCC	Committee on Climate Change
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
E&P	Exploration and Production
EIA	Economic Impact Assessment
EMEC	European Marine Energy Centre
EV	Electric Vehicle
FCV	Fuel Cell Vehicle
FES	Future Energy Scenarios
GDNO	Gas Distribution Network Operator
GDP	Gross Domestic Product
GVA	Gross Value Added
GW	Gigawatt
HGV	Heavy Goods Vehicle
IP	Core Intellectual Property
JIVE	Joint Initiative for Hydrogen Vehicles across Europe
kg	Kilogram
kW	Kilowatt
kWh	Kilowatt Hour
m	Million
MW	Megawatt
MWh	Megawatt hour
O&G	Oil and Gas
OEM	Original Equipment Manufacturer
OGA	Oil and Gas Authority
OGTC	Oil & Gas Technology Centre
OGUK	Oil & Gas UK
OpEx	Operational Expenditure
R&D	Research and development
SGN	Scotia Gas Networks
SME	Small to Medium Enterprise
SMR	Steam Methane Reforming
tn	Tonne
TWh	Terawatt hour
UKCS	UK Continental Shelf

TABLES AND FIGURES

EXECUTIVE SUMMARY

Hydrogen is set to play a key role in decarbonising the global energy system. Scotland's vast renewable resources, combined with its skills and supply chain focused on energy transition, are critical to establishing a prominent role for Scotland in the emerging global hydrogen market.

This report was commissioned by the Scottish Government in partnership with Highlands & Islands Enterprise and Scottish Enterprise and carried out by consultants Arup and E4tech. Global commitment to the deployment of hydrogen is accelerating, with national governments making increasingly ambitious commitments to the sector. Scotland will need to act decisively and provide clear policy support to position itself at the forefront of a growing a global industry.

The ultimate scale of hydrogen deployment in the energy system is uncertain and will depend on technology commercialisation pathways for both electrification and hydrogen options. A future energy system will see increased electrification. However, it is likely that another energy carrier will be required to enable a more flexible, resilient and integrated system, and hydrogen is increasingly seen as playing a complementary role to electricity.

The benefits of hydrogen for the energy system are becoming increasingly clear and the economic opportunity is significant. Scotland should focus on interventions in the hydrogen sector that are targeted and aligned with Scotland's skills and supply chain strengths. Policy should provide strong signals to industry, underpinning short to medium term investments and contributing to a post-COVID green economic recovery. Those investments will build the evidence base which informs the long term direction of travel. The Hydrogen Assessment Project engaged extensively with industry to develop three distinct and viable scenarios by which the Scottish hydrogen economy could develop out to 2045. These scenarios were used to understand the potential economic benefits associated with the production, transmission, supply and export of hydrogen.

In the most ambitious scenario, establishing Scotland as an exporter of green energy to Europe could result in a £25 bn contribution to Gross Value Added (GVA) with over 300,000 jobs by 2045. This would be achieved by unlocking Scotland's vast offshore wind potential, but would be dependent on Scotland producing green hydrogen that is competitive in a European market.

Supporting a domestic hydrogen market is likely to support anywhere between 70,000 to 175,000 jobs (£5-16 bn GVA) and is very dependent on the extent of the penetration of hydrogen in the energy system.

The following organisations were engaged to inform the Hydrogen Assessment Project.

Green hydrogen is produced using renewable electricity and is zero carbon. Blue hydrogen is produced by reforming natural gas in conjunction with carbon capture and storage and is low carbon.

THE SCENARIOS ARE:

	HYDROGEN ECONOMY	GREEN EXPORT	FOCUSED HYDROGEN
	Hydrogen is one of the main ways in which Scotland's energy system is decarbonised. A balanced mix of blue and green hydrogen is extensively across all sectors.	Scotland's vast renewable resources, particularly offshore wind, but also wave, tidal and onshore are used to produce green hydrogen. This serves a European export market.	Hydrogen plays a supporting role in decarbonising the energy system in sectors that are hard to decarbonise by other means. Hydrogen is produced near to where it's used.
PRODUCTION			
	46 TWh / 39 TWh	126 TWh	14 TWh / 7 TWh
END USE			
TRANSPORT	11 TWh	22 TWh	7 TWh
DOMESTIC AND COMMERCIAL HEAT	35 TWh	-- TWh	6 TWh
INDUSTRY AND ELECTRICITY	19 TWh	11 TWh	7 TWh
EXPORT	20 TWh	94 TWh	
GVA	£16 billion	£25 billion	£5 billion
JOBS	175,000	310,000	70,000

Investment in both green and blue hydrogen production will provide strong economic benefits to Scotland and contribute to its energy transition. While blue is likely to play a transitional role, green is expected to become increasingly dominant as costs reduce.

In the short term, investment in transport, particularly public sector and fleet, will create certainty of demand to support investment in production. Meanwhile, building the evidence base to determine the role for hydrogen in the gas network should be vigorously pursued.

GREEN HYDROGEN PRODUCTION AND SCOTLAND'S RENEWABLE INDUSTRY

Scotland's resources in onshore and offshore wind, wave and tidal are vast, hydrogen has potential to unlock more of these renewable resources and improve the competitiveness of Scottish renewables. The evidence base assessment and stakeholder engagement indicated that Scotland could be an exporter of hydrogen to energy scarce countries in Europe, such as Germany, which has declared an intent to import green hydrogen. However, this would be reliant on Scotland's ability to produce hydrogen that is cost competitive in an international market.

In this assessment, production of green hydrogen for export and domestic use provided the greatest additionality in terms of GVA and employment, with an estimated £19 bn of value-added and nearly 220,000 jobs in 2045. The engagement and evidence base suggests that the required skills frequently align with those already present in the renewable and offshore industries. Capturing more of the green hydrogen production value chain, including electrolyser integration or even manufacturing upstream would result in greater economic benefits.

However, Scotland has a limited pipeline of green hydrogen production projects, and there are gaps in the indigenous supply chain. Support from Government, both in terms of stimulating a market and investing in skills and supply chain, is needed.

BLUE HYDROGEN PRODUCTION AND SCOTLAND'S ENERGY TRANSITION

Blue hydrogen coupled with carbon capture utilisation and storage (CCUS) offers strong opportunities for transition of the oil and gas (O&G) industry. It is likely to be lower cost than green hydrogen until costs reductions for green are realised. However, it will be a transition technology, given it is not zero carbon, and its role will likely reduce by 2045.

Many of the supply chain elements required for blue and green hydrogen production and CCUS already exist in Scotland's O&G industry, and will be employed in the delivery of Scotland's flagship blue hydrogen and CCUS project: Project Acorn.

TRANSPORT SECTOR

Hydrogen offers significant advantages over electric vehicles (EV) in heavy fleet vehicles such as buses, heavy goods vehicles (HGVs), non-electrified trains and ferries. Use of hydrogen vehicles in these favourable modes could be encouraged in the short to medium term to drive demand certainty, and to ensure rapid decarbonisation.

BUILDINGS AND HEATING

The flexibility and storage potential offered by hydrogen could be key to addressing inter-seasonal heating demand. The existing gas distribution network could be repurposed to hydrogen, potentially easing the transition from natural gas. However, the evidence base must be developed to support longer term decisions on the future for hydrogen in the gas network. If the indicators are positive, the use of hydrogen in domestic, commercial and industrial space heating could to play an important role in unlocking blue hydrogen production.

INDUSTRY AND POWER GENERATION

Hydrogen is already used in industry as a feedstock, but its use could be significantly expanded. Industrial use could generate the scale of demand required to create blue hydrogen hubs in conjunction with CCUS. It is anticipated that both blue and green hydrogen could both be used in industry. Current natural gas power generation could be replaced by hydrogen generation in order to support peak electrical demand, though this is likely to play a more modest role in peaking plants given the amount of renewables in Scotland.

Public and private sector support for hydrogen is strong, and industry is seeking to work closely with government to position Scotland to build on existing skills and natural resources and secure economic benefits from the hydrogen economy.

As part of the Hydrogen Assessment Project, a wide range of organisations were consulted on their views on the development of hydrogen in Scotland. Key emerging themes include:

SCOTLAND COULD GROW A STRONG HYDROGEN ECONOMY SUPPORTING JOBS AND GVA GROWTH

Value can be captured through investing in innovative technology, manufacturing and infrastructure. Production of hydrogen, particularly green, provides strong potential for GVA additionality, but there are gaps in the supply chain that must be filled to ensure Scotland maximises benefits from the transition.

CO-ORDINATION OF EFFORTS ACROSS INDUSTRY AND GOVERNMENT

Will enable an efficient transition and ensure economic opportunities are maximised. Stakeholders suggestions included public sector investment, alignment of regulation, creation of a body co-ordinating innovation and research, and a public-private sector leadership steering group.

CLEAR STRATEGY WITH PROPOSED AMBITIONS

Stakeholders were clear in their desire for Scotland to develop a well-defined policy environment, setting out its proposed ambition for hydrogen, aligned with its workforce and natural capital. This will give a clear signal of ambition and provide industry and investor confidence.

GOING BEYOND THE PILOT PROJECT STAGE AND INTO COMMERCIAL SCALE PROJECTS

To move beyond the small pilot stage and progress to larger scale commercial projects, industry requires viable business models that allow for and stimulate private sector investment. Expediting the implementation of an enduring fiscal regime will be critical to creating the pipeline of post demonstration projects.

MAINTAINING FLEXIBILITY

Hydrogen is still in the early stages as an energy carrier and ruling out options now would be premature, in the context of seeking net-zero 2045 solutions.

Demand applications that are low regrets should, where possible, be moved to commercial deployment in the short term. For others, more development and demonstration are required to create an evidence base which will inform the optimal applications.

HYDROGEN NEEDS TO BE SEEN WITHIN A WHOLE ENERGY SYSTEM CONTEXT

Hydrogen will complement increasing electrification, by improving system flexibility and resilience. Some of its benefits will only be understood when looking at the wider system context.

SPEED OF DEPLOYMENT

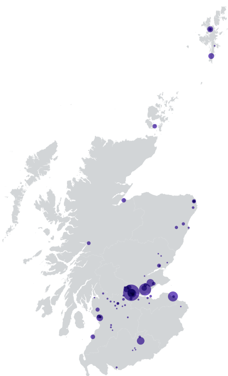
Is important if Scotland wants to capture more of the economic value from hydrogen activities. Scotland could become a centre for the production and export of green hydrogen and associated skills, products and services. If Scotland is slow to deploy, then there is a risk that more of those skills and manufacturing will be developed quicker elsewhere, leaving Scotland at a disadvantage.

Hydrogen has a role to play in all Scotland's regions, with its application reflecting the distribution of resources and geography specific demands. Island and rural communities, industrial clusters and urban areas are already developing solutions and expertise appropriate to their natural capital and energy needs.

Hydrogen solutions in Scotland are likely to be region specific, reflecting local resources and demands, as current Scottish demonstration and development projects show:

ISLAND AND RURAL COMMUNITIES benefit from the collocation of green hydrogen supply and demand, which can accelerate decarbonisation. High fuel costs and constrained infrastructure mean hydrogen projects are more likely to be economically viable and can realise more socio-economic benefits to those communities.

These areas may also offer opportunities to become hubs for hydrogen export to Scotland, UK and Europe, as they link resource to production with onward distribution. The Orkney Islands are making significant progress in realising these opportunities and other regions like Shetland and the Outer Hebrides are following suit.



INDUSTRIAL CLUSTERS involve difficult to decarbonise activities, some of which are already hydrogen users, such as the Grangemouth refinery and Mossmoran chemical plant. Blue hydrogen production can have synergies with industrial decarbonisation where CCUS is already required to reach net-zero. Both CCUS and blue hydrogen draw heavily on existing O&G sector skill sets and offer strong potential for transition and diversification. Acorn CCUS in St Fergus is an anchor project that can support industrial decarbonisation, while the Acorn blue hydrogen project can support industry fuel switching and supply hydrogen into the national grid transmission system.

URBAN AREAS are tackling challenges of decarbonisation and improving air quality. Dense population and extensive infrastructure provide opportunities for scale economies from aggregating demand. Switching public sector transport and back to base fleet vehicles to hydrogen could create the certainty of demand that stimulates investment in hydrogen production. It may even stimulate some assembly or manufacturing, although this is likely to depend on the application scale of demand and global market development. In the longer term, conversion of urban gas networks may allow for decarbonisation of domestic and commercial heat demand. Aberdeen, recently described by the Scottish Government as a Hydrogen Model Region, has paved the way as an early adopter of hydrogen buses, with longer term ambition in wider transport and heat applications.

1.

INTRODUCTION AND POLICY CONTEXT

1 INTRODUCTION AND POLICY CONTEXT

1.1 NET-ZERO AND A HYDROGEN PATHWAY

The Scottish Government is committed to achieving net-zero by 2045[1]. To date, most of Scotland's emissions reductions have come from decarbonisation of electricity generation. Solutions to decarbonise heat, industry and transport are now growing priorities which will require a broader range of technologies, strategies and energy systems solutions.

There is broad consensus that hydrogen will play a critical role in decarbonisation of the energy system. Key policy and publications such as the Scottish Energy Strategy (2017)[2], Committee on Climate Change (CCC) Net Zero report (2019)[3,4] and National Grid ESO's Future Energy Scenarios (FES) 2020[5] have identified hydrogen as vital in decarbonising the energy system. Within these, hydrogen generally plays a role in decarbonising sectors where electrification is challenging.

Identifying the unique Scottish context and understanding hydrogen's role in decarbonisation is critical to informing the policy framework and interventions necessary to achieve Scotland's ambitious decarbonisation targets.

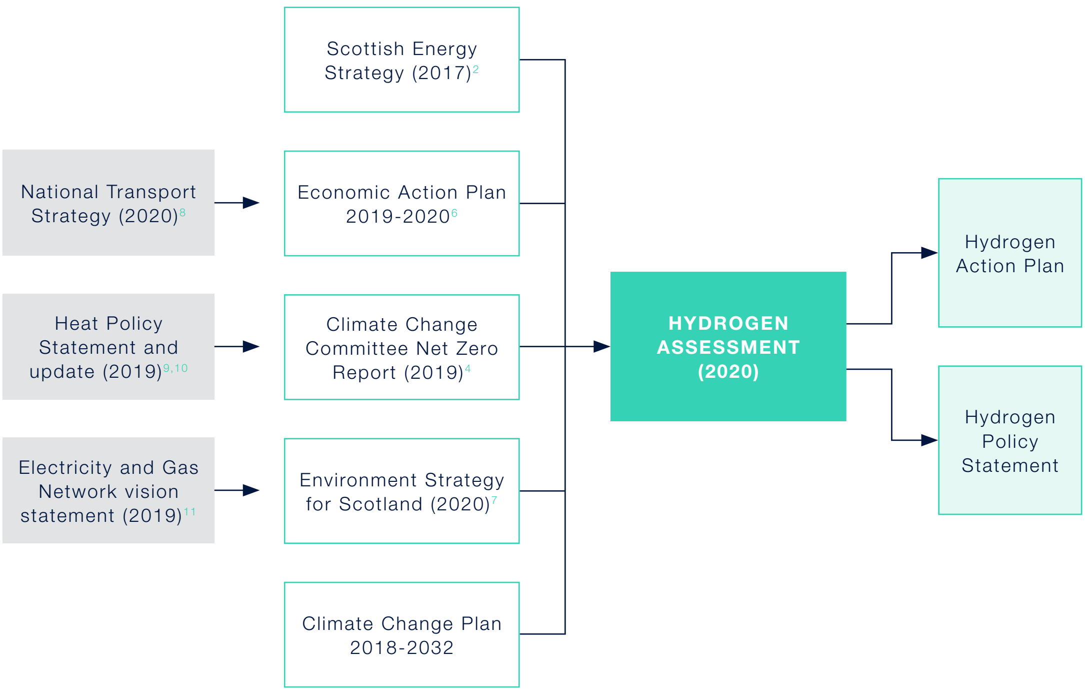
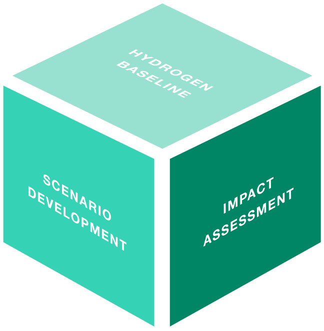


Figure 01: Developing Scottish and UK policy context for hydrogen[6, 7, 8, 9, 10, 11]

1.2 SCOTTISH HYDROGEN ASSESSMENT

This Scottish Hydrogen Assessment will inform the development of future Scottish Government decarbonisation policy. It will form an important part of the evidence base for the development of the Hydrogen Policy Statement and Hydrogen Action Plan committed to in the Programme for Government 2019-20[12].

This assessment aims to investigate how and where hydrogen may fit within the evolving energy system technically, geographically and economically. To assist in this consideration, a key part of the Hydrogen Assessment is the development of distinct viable scenarios for hydrogen deployment in Scotland and the economic assessment of those scenarios.



- Describes the context for hydrogen in Scotland considering skills, supply chain, resources, and infrastructure.
- Set out three distinct pathways by which hydrogen could be deployed in the Scottish energy system out to 2045.
- Considers the economics benefits associated with each scenario.

Figure 02: Three phases of the Hydrogen Assessment

1.3 STAKEHOLDER ENGAGEMENT

The Hydrogen Assessment was supported by extensive stakeholder engagement focused on a selection of key organisations likely to be involved in the future hydrogen sector, both in Scotland and further afield.

Figure 03: Selection of stakeholders consulted

This engagement was designed to gather thoughts and views on the options for hydrogen production, transportation and end use in Scotland. This fed into the design and development of the scenarios, through which these options could be fully explored (see Section 6 for the scenarios). Engagement was conducted over a number of months and set out in four phases.

Initial focused group sessions to develop ideas and concepts for the scenarios.	**FOCUSED GROUP SESSIONS**	Six webinars 24 organisations
Stakeholder survey on the status of hydrogen in Scotland and how it could be developed in the future.	**SURVEY**	Comprehensive survey 38 detailed responses
A series of focus group session undertaken to elicit feedback on the short listed scenarios and to provide test and challenge on the detailed assumptions.	**SCENARIO SESSIONS**	Three sessions 15 organisations
Finally, a range of one-to-one interviews with senior figures in the energy industry including Sir Ian Wood (Opportunity North East (ONE)), Chris Stark (CCC), and Collette Cohen (Oil & Gas Technology Centre (OGTC)).	**ONE TO ONES**	11 interviews 11 organisations

Figure 04: Stakeholder engagaement process

1.4 HYDROGEN IN THE ENERGY SYSTEM

As the first element in the periodic table, hydrogen is the simplest, the lightest and the most abundant element in the universe. Hydrogen does not commonly exist in its pure form on Earth, and is typically found with other elements, for example, water (H_2O). Hydrogen and carbons form hydrocarbons which we think of as fuels (e.g. methane CH_4). To be used in the energy system hydrogen needs to be produced from other sources with water and methane being the most commonly used.

Hydrogen production and use within the energy system is not a new concept. The earliest forms of large scale production via electrolysis date back to the 1900s. Hydrogen was a key constituent of 'towns gas', which powered a significant amount of Scotland's heating and street lighting systems until the discovery of North Sea natural gas.

More recently, hydrogen has become of interest as a decarbonisation option as it emits no carbon dioxide at the point of use. It can support sectors where it is difficult to reach net-zero with just electricity. Hydrogen, like electricity, is considered an energy carrier i.e. it is produced to allow the storage and transfer of energy, rather than a primary source like natural gas, oil, coal etc. Hydrogen can be used widely across parts of the energy sector as seen in Table 1. Currently, the majority of these areas are served by carbon intensive fossil fuels.

"The key technologies required for hydrogen production are already available, however further development will reduce costs and improve performance"

Stakeholder questionnaire opinion

CATEGORY	DESCRIPTION
Production	Grey hydrogen – hydrogen produced from reforming natural gas. This process produces both hydrogen and carbon dioxide.
	Blue hydrogen – hydrogen produced from reforming natural gas, as for grey hydrogen. However, in this case around 95% of the carbon dioxide produced is captured and stored through Carbon Capture Utilisation and Storage (CCUS) technologies. Blue hydrogen could also be produced using biogas. This could potentially act as a carbon sink to offset sectors that cannot reach zero emissions.
	Green hydrogen – hydrogen produced by splitting water in an electrolyser powered from zero carbon sources. This process produces hydrogen and oxygen. No carbon dioxide is released.
Transportation	Pipelines, hydrogen delivery vehicles or vessels.
Storage	Above ground or geological.
End usage	Including in transport, domestic & commercial heating, industrial heating & processes and power generation. These applications can be either fuel cell or direct combustion.

Table 01: Application of hydrogen

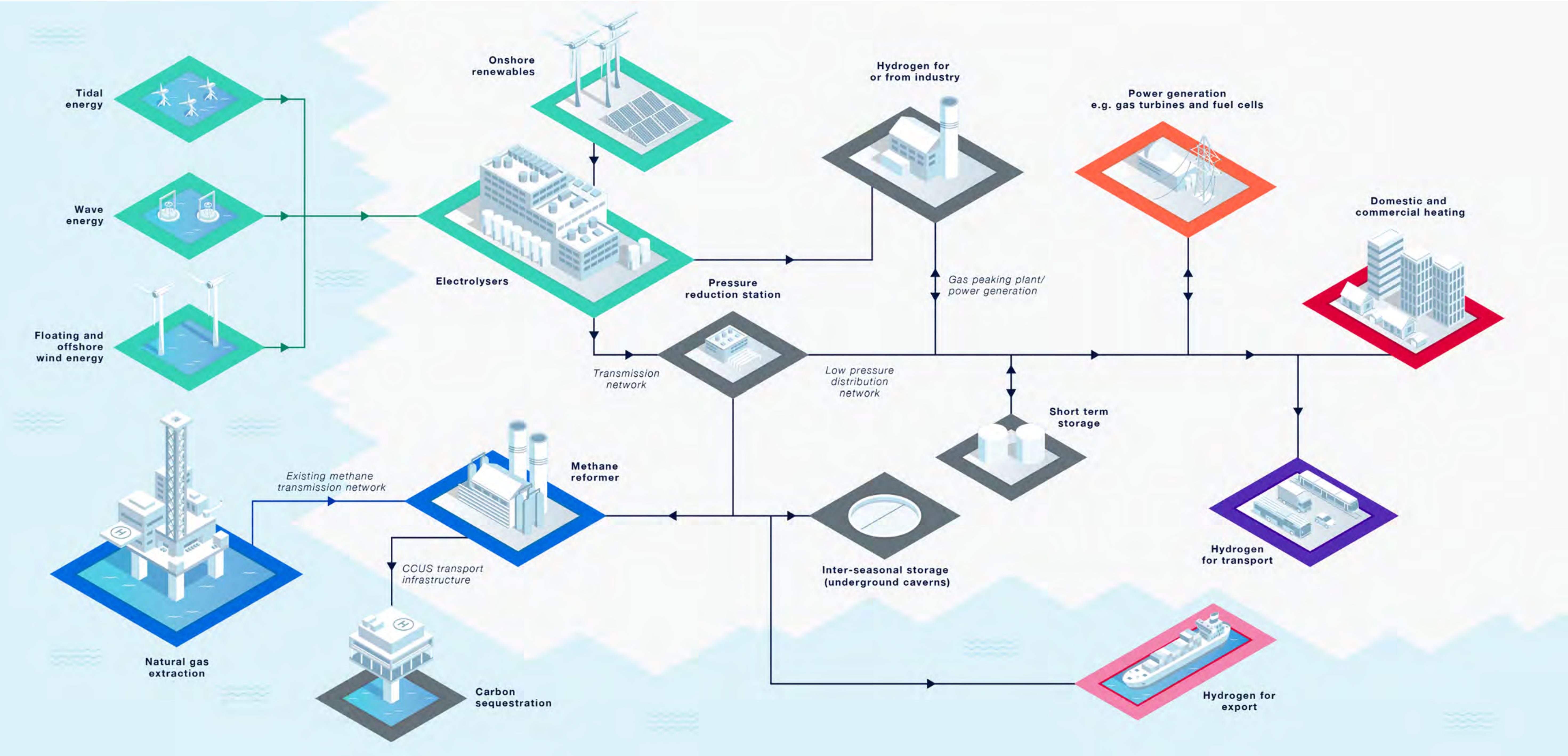


Figure 05: Example hydrogen energy system

2.

THE GLOBAL PICTURE FOR HYDROGEN

2 THE GLOBAL PICTURE FOR HYDROGEN

2.1 GLOBAL ACTION

Momentum is building internationally for hydrogen to play a key role in a future decarbonised energy system. Within Europe and globally, nations are developing hydrogen strategies and policy frameworks, to set out their national ambitions. These are generally supported by targets and clear plans for action, which are summarised in Table 2.

Scotland is not alone in pursuing hydrogen but has been at the forefront of hydrogen demonstration and development. In order to maintain that position in a fast-moving global market, it is critical that action is taken to set clear and ambitious targets and policy frameworks for the sector, that are aligned with its natural capital and unique strengths.

> *"Those with the most developed industrial economies such as Japan and Germany have a clear lead in traditional hydrogen applications such as refining, steelmaking, steelmaking, chemical processes etc"*
>
> Stakeholder questionnaire opinion

Globally a range of actions have been undertaken to support the hydrogen economy. Some have included supporting demonstration projects, to provide the evidence base to de-risk commercial deployments. Others have provided wider market support, to enable commercial deployment at scale. The last decade has seen a significant expansion of activity and projects in the hydrogen sector. Activity is particularly clustered around South East Asia and Europe, although there is interest in the US and elsewhere. Figure 7 and Figure 8 show a selection of global and European hydrogen projects respectively.

EUROPEAN UNION[13] (STRATEGY RELEASED JULY 2020)

TARGETS AND COMMITMENTS

6 GW of green hydrogen electrolysers by 2024, and min. 40 GW by 2030

European Clean Hydrogen Alliance to facilitate the strategy actions and build an investment pipeline.

Fuel Cells and Hydrogen Joint Undertaking (FCHJU) drives a funding scheme (€1.3 billion (bn)) to accelerate hydrogen technologies in energy and transport[14].

KEY DRIVERS

Decarbonisation

European Green Deal call under Horizon 2020 (Q3 2020). Just Transition alignment

Enables renewable energy development

Mix of green and blue hydrogen production.

Green hydrogen is the priority, with blue hydrogen needed in the interim.

CHALLENGES IDENTIFIED

International policy commitments

Large scale system integration and cooperation

Requires critical mass in investment

GERMANY[15] (STRATEGY RELEASED JUNE 2020)

TARGETS AND COMMITMENTS

5 GW of green hydrogen generation by 2030.

€7 bn to ramp up “home market” and a further €2 bn to invest in partner country production.

KEY DRIVERS

Green decarbonisation

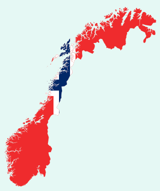
Focus on green hydrogen production, but recognise a EU market for blue hydrogen as transition.

CHALLENGES IDENTIFIED

Domestic hydrogen production (drives needs for imports) and cross-border collaboration

Negative public opinion on blue hydrogen production.

NORWAY[16] (STRATEGY RELEASED JUNE 2020)



TARGETS AND COMMITMENTS

Increase the number of pilot and demonstration projects. Focus on transportation and industry.

ENERGIX- programme grant of NOK 120 million (m) (€11 m*). Hydrogen technologies have central role in the programme.

KEY DRIVERS

Decarbonisation

Economic value creation

Mix of green and blue hydrogen production.

CHALLENGES IDENTIFIED

Targets relying on technological progress

NETHERLANDS[17] (STRATEGY RELEASED MARCH 2020)

TARGETS AND COMMITMENTS

Hydrogen programme to develop 3-4 GW of electrolyser capacity by 2030.

NorthH2 vision launched in February 2020 which intends to produce green hydrogen from offshore wind, growing to 10 GW in 2040[18].

€35 m/year Climate Budget Fund, some of which will be allocated to support scaling up operating costs of various technologies, including hydrogen related ones.

Energy Innovation Demonstration Scheme- maximum of €15 m per project of which hydrogen projects are eligible.

Renewable energy subsidy scheme that includes hydrogen production via electrolysis (maximum €300/tonne (tn) produced)

KEY DRIVERS

Decarbonisation

Large wind energy resource including offshore

Transition away from natural gas production

Mix of green and blue hydrogen production

CHALLENGES IDENTIFIED

Decarbonising current grey hydrogen production supplying industry

Setting up a hydrogen supply chain to capture economic benefits

Table 02: Summary of international hydrogen strategies

		TARGETS AND COMMITMENTS	KEY DRIVERS	CHALLENGES IDENTIFIED
AUSTRALIA[19] **(STRATEGY RELEASED NOVEMBER 2019)**		Targeting exports to Asia. Phase 1 (underway to 2025) focused on demonstrations. Phase 2 large scale market activation (2025 onwards). Government has already committed over AU$146 m (€88 m*) to hydrogen projects along the supply chain. Regional boosts e.g. AU$15 m (€9 m*) Hydrogen Industry Development Fund in the Queensland Hydrogen Strategy.	Large scale wind and solar resources. Opportunity to export hydrogen to Japan and Korea. Decarbonisation of indigenous heavy industry and heavy transport. Focus placed predominately on green hydrogen production.	Demonstrating the safety case. Development of early demand.
SOUTH KOREA[20] **(ROADMAP RELEASED 2019)**		Focused on transportation. Target of 6.2 m fuel cell vehicles (FCV) and 1,200 refuelling stations by 2040[21] In 2018 the Ministry of Trade Industry and Energy (MOTIE) announced US$ 22 bn (€18.5 bn*) budget for establishment of a hydrogen vehicle industry[22]	Economic opportunities in automotive manufacturing. Mix of green and blue hydrogen production.	Planned rapid increase in demand, low capability for indigenous production.
JAPAN[23,24] **('BASIC' HYDROGEN STRATEGY, 2017)**		Focused on transportation due to large automotive manufacturing industry. Target of 800,000 FCVs by 2030. Olympic village has 6,000 residential units supplied exclusively by hydrogen, through combined heat and power fuel cell. The Japanese government have previously dedicated US$1.5 bn (€1.27 bn*) to hydrogen technology research and development (R&D).	Current reliance on fossil fuel imports Energy security Shift away from nuclear following Fukushima disaster Decarbonisation Automotive manufacturing capability Mix of green and blue hydrogen	Economic efficiency related to cost competitiveness of hydrogen technologies and competing automotive hydrogen markets.
CHINA[25] **(NO STRATEGY RELEASED)**		Focused on transport applications. Target of 1 m FCVs by 2030 and 1,000 refuelling stations. Recently announced construction start of world's largest solar powered hydrogen plant in Nigxia Hui[26].	Decarbonisation. Competitiveness in automotive manufacturing. Improving air quality. Mix of green and blue hydrogen.	Lack of domestic resource to create components used in hydrogen technology e.g. fuel cells, electrolysers.
USA[15] **(STRATEGY RELEASED JULY 2020)**		Focused around fuel cells for transportation and power. E.g. the California Hydrogen Highway, one of the largest refuelling networks globally.	Decarbonisation. Support manufacturing industries. Mix of green and blue hydrogen.	Cost efficiency. Safety case development and lack of public awareness. Institutional barriers.

Table 02: Summary of international hydrogen strategies (continued)

2.2 A GLOBAL COMMODITY MARKET

As with all energy resources markets appear through energy imbalance. Countries with abundant resources relative to demand have the potential to be net exporters e.g. Australia, Scotland, and vice versa will be importers e.g. Germany. Hydrogen could be a global energy commodity, acting as an energy carrier, with strong analogies to the existing global O&G market.

For a country to be a successful exporter of hydrogen, it must be able to produce and transport the hydrogen to the point of demand. This must be done in a cost competitive way, competing in a global market. Access to low cost renewables, supplies of natural gas, carbon storage infrastructure, utilisation of existing transport infrastructure and proximity to demand, will all contribute to reducing the cost base.

The international hydrogen commodity market is in its infancy but could develop rapidly. For example, energy scarce Japan has secured hydrogen supplies from Australia for the Tokyo 2021 Olympics.

Scotland is well placed in terms of proximity and infrastructure connectivity to several European import nations, such as Germany, Italy, the Netherlands, Belgium and Sweden. These countries are unlikely to be able to decarbonise wholly through their indigenous wind and solar renewable energy supply. Scotland also has potential to produce significant quantities of green hydrogen from an offshore wind resource, which is vastly greater than its indigenous demand. However, competition is expected from regions such as the Middle East and southern Europe where very cheap solar electricity has the potential to create very low cost green hydrogen.

> *"Scotland could make significant profit from exporting hydrogen to England and the rest of Europe"*
>
> Stakeholder questionnaire opinion

Estimates of the scale of the global market vary and will ultimately depend on the level of penetration of hydrogen within the energy system. Figure 6 shows a range of predicted demand level in 2050 globally, in Europe and in the UK.

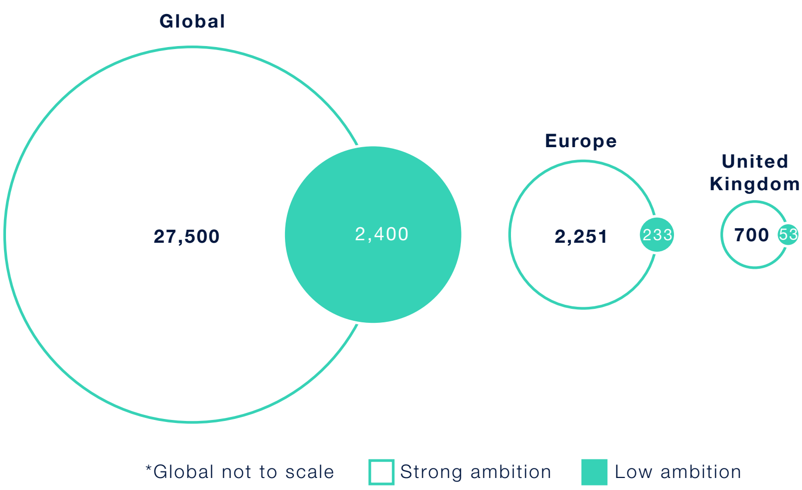


Figure 06: Predicted hydrogen demand (TWh) in 2050[13, 14, 15, 16]

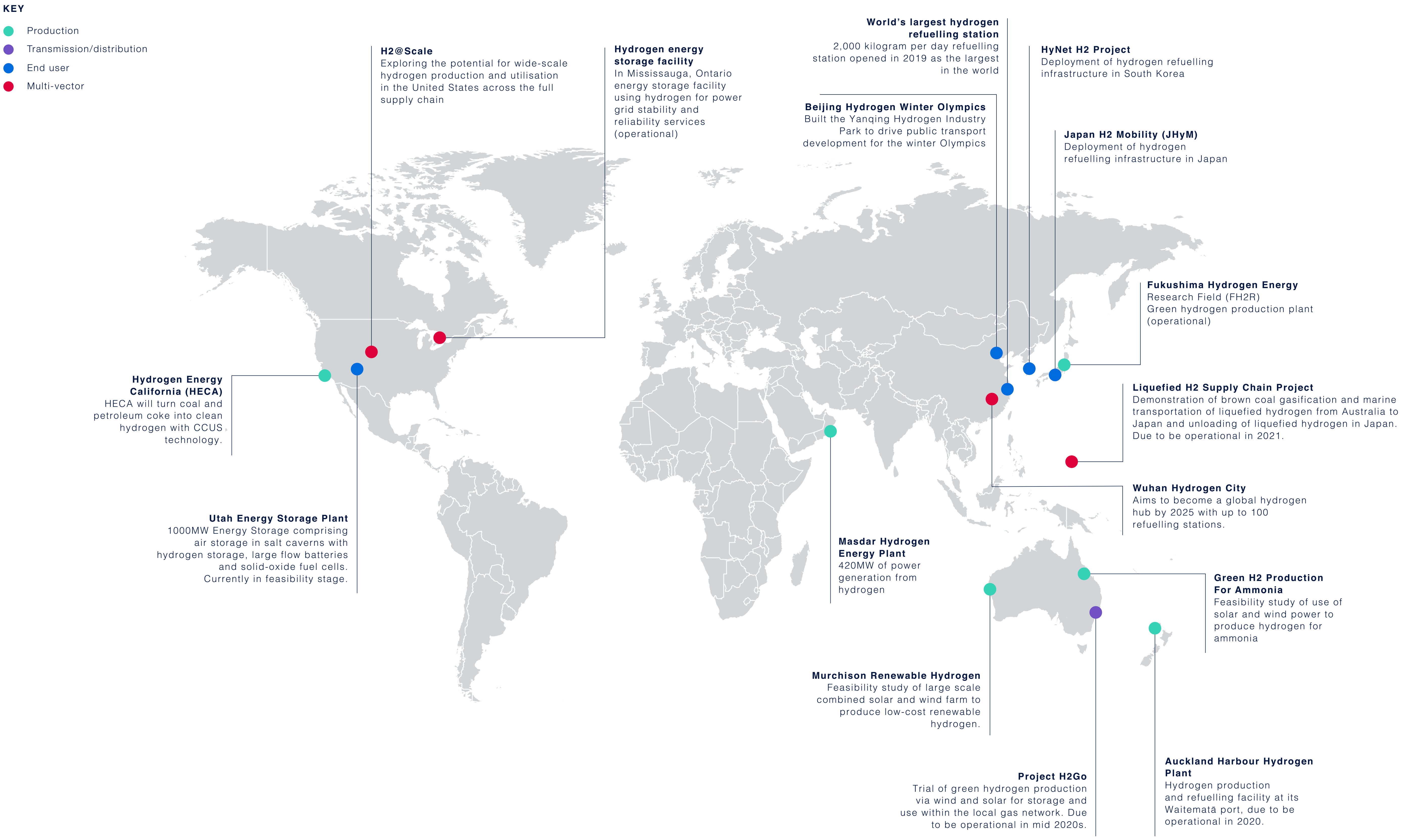


Figure 07: Examples of hydrogen projects globally

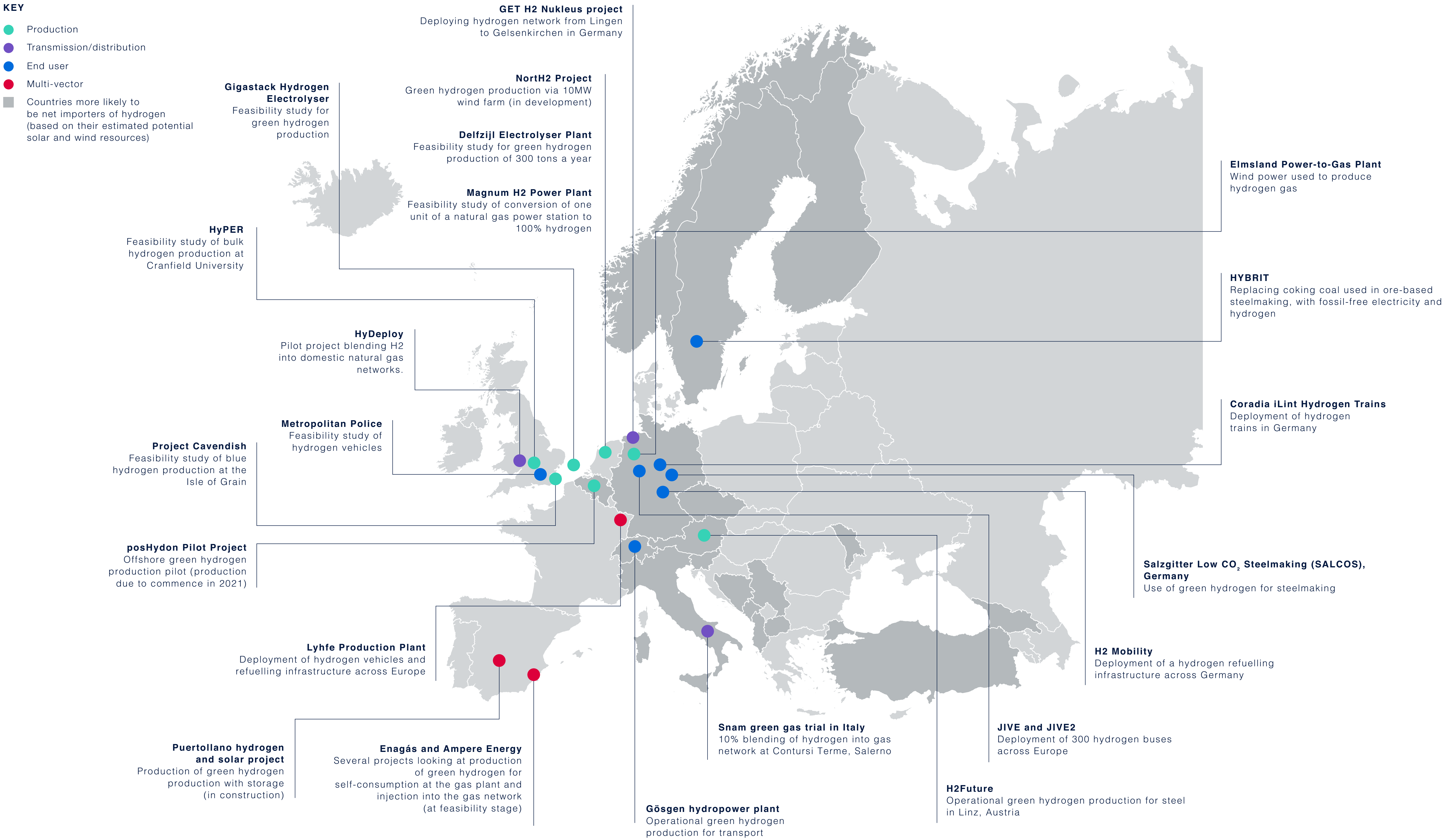


Figure 08: Example hydrogen projects in Europe

CASE STUDY: GERMANY'S NATIONAL HYDROGEN STRATEGY

Germany's national hydrogen strategy[17] was approved by Ministers in June 2020. It highlights a focus on green hydrogen production and indicates Germany is set to be a large scale importer of hydrogen.

The strategy includes €7 bn to ramp up hydrogen technologies developing a "home market" and a further €2 bn to invest in large scale production plants in partner countries. It includes a target of generation plants with a total capacity of up to 5 gigawatt (GW), supplied by offshore and onshore renewable energy generation, by 2030. This corresponds to a green hydrogen production of up to 14 terawatt hours (TWh). The key aims of the strategy is:

- Assume global responsibility in **emissions reductions** by establishing hydrogen as a decarbonisation option.
- Make hydrogen competitive by pushing **cost reductions** into a fast-moving international market ramp-up.
- Develop a **'home market'** to pave the way for imports.
- Establish hydrogen as an alternative energy carrier to **decarbonise hard-to-abate sectors**.
- Make hydrogen as a raw material for **industry sustainable** by switching current fossil fuel based production to renewable energy production.
- **Enhance transport and distribution infrastructure** using existing gas infrastructure and extending dedicated hydrogen networks or building new ones if required.
- **Support research** and train qualified personnel.
- Strengthen the German economy and **secure global market opportunities** for German companies.
- Understand **global cooperation is an opportunity** and establish international hydrogen markets, as sizeable imports will be required in medium and long term.

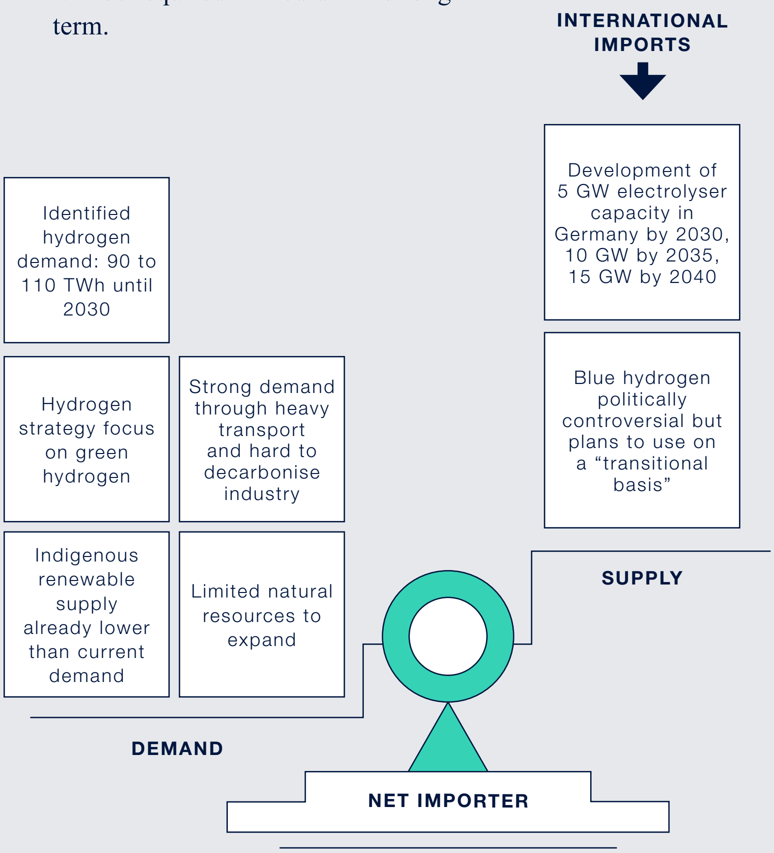


Figure 09: Hydrogen supply and demand balance of Germany

CASE STUDY: AUSTRALIA'S NATIONAL HYDROGEN STRATEGY

Australia agreed a National Hydrogen Strategy in November 2019[18]. The aim of the strategy is to position Australia firmly within a global hydrogen market by 2030. Australia plans to produce green hydrogen using its abundance of natural capital from wind and solar resources. The strategy highlights that Australia would be a net exporter to countries such as Japan and Korea, which are anticipated to be net importers.

Australia has taken an 'adaptive pathway' including two phases: a foundations and demonstrations phase (underway to 2025) and a large scale market activation phase (from 2025 onwards)[18]. The strategy outlines four key measures of success:

1. Australia being one of the top three hydrogen exporters to Asian markets.
2. Hydrogen providing economic benefits and jobs in Australia.
3. Australia having a robust, internationally accepted provenance certification scheme.
4. Australia demonstrating an excellent hydrogen related safety record.

The strategy includes a number of enabling actions[18]:

- A National Hydrogen Infrastructure Assessment which considers the hydrogen supply chain needs and is reviewed and updated at least every five years.
- Support pilot and trials for blending hydrogen in gas distribution networks.
- Plans to implement a recognised certification scheme to provide a guarantee to potential international importers of Australian hydrogen on the origin of that hydrogen (e.g. green hydrogen produced from solar).
- Bilateral partnerships to promote trade and investment in hydrogen.
- National coordination including an annual 'State of Hydrogen' report to be published by the Commonwealth Government.

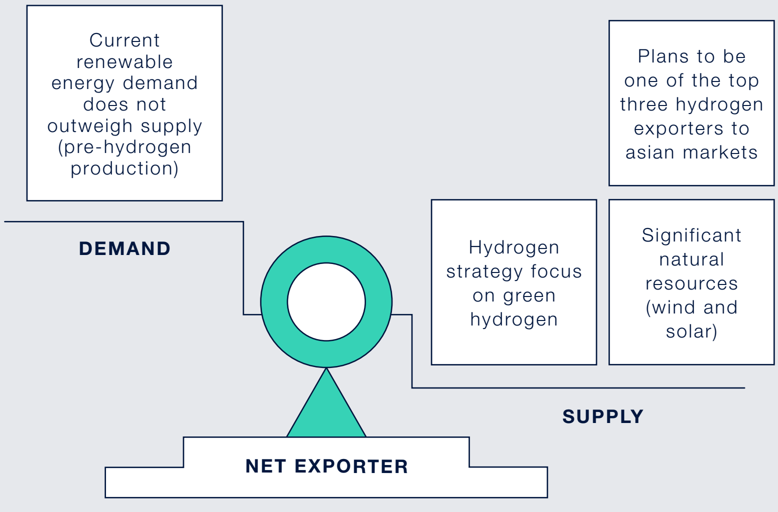


Figure 10: Hydrogen supply and demand balance of Australia

3.

A SCOTTISH HYDROGEN ECONOMY

3 A SCOTTISH HYDROGEN ECONOMY

3.1 SCOTLAND'S POTENTIAL

The Scottish hydrogen story is not just about the potential to decarbonise. It is about using Scotland's natural capital to achieve the Scottish Governments stated aim "*to achieve a Just Transition to net zero, by ensuring everyone can benefit from the opportunities and no one is left behind*" and a green economic recovery post Covid-19. Scotland has a range of competitive advantages which can enable an ambition to secure an influential role in a global hydrogen economy.

More broadly Scotland represents an attractive location for investment opportunities in the energy sector. It has a stable planning regime, energy policy, government support, skilled workforce, good infrastructure, a mix of industrial, commercial and domestic demands, limited constraints on water resources, and a track record in research and innovation.

GREEN HYDROGEN

Scotland's renewable energy potential is much greater than indigenous demand. When considered in the context of its proximity to potential European export markets, such as Germany, and the existing O&G import and export infrastructure, this provides a significant export opportunity.

DIVERSITY AND RESILIENCE

The two complementary hydrogen production sources (blue and green) could provide Scotland a resilient hydrogen supply. It has the potential to match the right production method, to the appropriate application and opportunities. Thereby creating energy transition pathways and green recovery with each technology playing different roles over time.

ENERGY SKILLS

Scotland has a long heritage in developing and exporting energy skills across sectors. Scotland's global recognition in O&G and renewables skills can provide the foundation of transition into a hydrogen economy that supports an indigenous and global market.

BLUE HYDROGEN AND CCUS

There are significant geological stores in the North Sea with potential to store carbon, a critical enabler in the production of blue hydrogen. Scotland has the potential to play a key role in a European carbon capture utilisation and storage (CCUS) market, which is critical for industrial decarbonisation and will have strong synergies with a blue hydrogen market.

Figure 11: Scotland's competitive advantages.

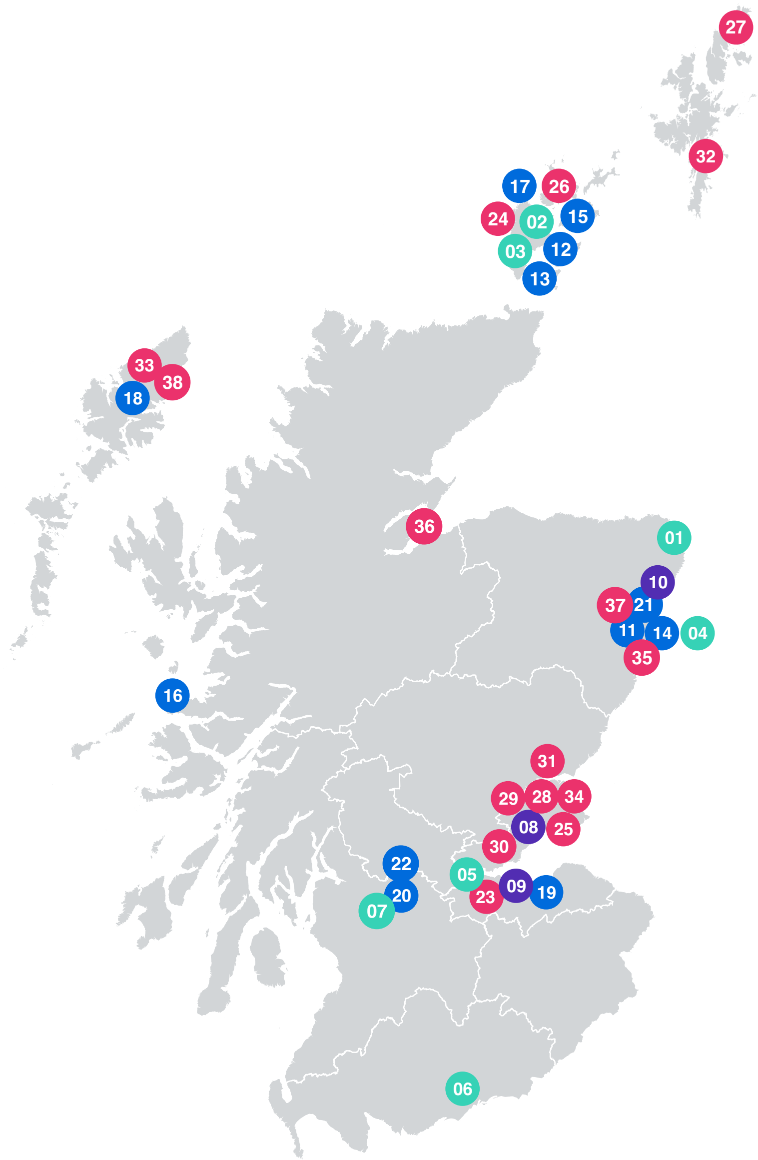
3.2 SCOTLAND'S EXPERIENCE

There is rapid acceleration of a hydrogen economy globally, with several nations developing and delivering on hydrogen strategies that match their existing strengths and natural capital. Scotland has already made significant progress on the global stage in creating the foundations of a transition, with a number of world leading demonstration and development projects. In order to maximise the captured economic benefits, Scotland will need to accelerate support and commitment in areas that match Scotland's strengths.

There is a clear and strong appetite from industry to develop and commercialise a hydrogen industry in Scotland, including comprehensive demonstration and early commercial projects in development, construction and operation, shown in Figure 12 and detailed in Appendix A1.1. Scotland's innovative, agile, entrepreneurial, and community led skills can be best seen in the aspirations of the Scottish Islands including Orkney and the Western Isles.

> *"The supply chain in Scotland which currently services heavy industry and the energy sector should be well positioned to support progress in the hydrogen industry. These supply chain lines have shown a prior ability to reshape themselves to support new industries (e.g. offshore wind), although as ever governmental support for this transition and a focus on encouraging local content will be key"*
>
> Stakeholder questionnaire opinion

- 01 Project Acorn
- 02 Hydrogen Offshore Production Project
- 03 Surf 'n' Turf
- 04 Dolphyn ERM
- 05 Caledonian Clean Energy Project
- 06 Chapelcross
- 07 Green hydrogen for Scotland
- 08 H100
- 09 Grangemouth to Granton future local transmission system
- 10 Aberdeen Vision
- 11 Hydrogen Bus Project
- 12 HySeas I - III
- 13 HySpirits
- 14 HyTrEc
- 15 HyDIME
- 16 SWIFTH2
- 17 HyFlyer
- 18 Stornoway hydrogen refueler
- 19 Hydrogen refuelling station
- 20 Glasgow hydrogen transport project
- 21 TECA fuel cell
- 22 Glasgow hydrogen bus project
- 23 HyStorPor
- 24 BIG HIT
- 25 Methilltoune
- 26 REFlex
- 27 Promoting Unst Renewable Energy
- 28 The Hydrogen Office
- 29 Levenmouth Community Energy Project
- 30 East Neuk Power to Hydrogen
- 31 Michelin Scotland Innovation Parc
- 32 Shetland Hub
- 33 100% Green Hydrogen Hub
- 34 Hydrogen Accelerator
- 35 Aberdeen Hydrogen Hub
- 36 Cromarty Firth Hydrogen Hub
- 37 Energy Transition Zone
- 38 Outer Hebrides Local Energy Hub



KEY

- Production
- Transmission/distribution
- End user
- Multi-vector

Figure 12: Hydrogen projects in Scotland

3.3 SCOTLAND'S REGIONAL SOLUTIONS

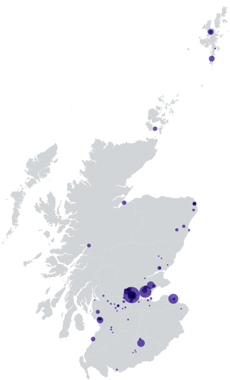
The deployment of hydrogen in Scotland is likely to be region and geography specific, reflecting the location of production resources, existing infrastructure and demand patterns. The trends in region specific solutions are reflected in the emerging demonstration and development projects shown in Figure 12 with distinct characteristics in island and rural locations, industrial clusters and urban centres.

Hydrogen offers an opportunity for **rural and island** communities, where a whole systems approach could allow efficient decarbonisation, while creating local economic benefits.

Scotland's island and rural locations have access to vast renewable resources. Despite this, they suffer from high fuel costs resulting in high levels of fuel poverty. This is due to a combination of factors including constrained electricity grids, limited penetration and/or interconnection of gas grids and the high costs of transporting fuel. High fuel prices and carbon intensive fuels, have a negative impact on energy intensive industries and commercial activities such as the whisky and distilling sectors.

An integrated energy system that includes hydrogen can allow better local management of supply and demand, allowing an increasing penetration of renewables in the system. Examples of this approach are emerging in the Western Isles and Orkney where hydrogen is being developed as a solution that can supply an increasing diversity of demands alongside increasing electrification.

In addition, proximity to large scale offshore renewables, may allow islands and rural locations to play a key role in production and export of hydrogen to the rest of Scotland, UK and Europe.



Scotland's **industrial clusters** represent numerous co-located and localised heavy industry units with diverse processes including chemicals, petrochemicals/refineries, manufacturing, food and drink, cement, paper and pulp, and glass.

These processes are often difficult to decarbonise as they have limited options in terms of low carbon solutions. This is particularly the case where a high temperature is required or a specific feedstock is essential for the chemical process. Some of Scotland's industrial clusters already have grey hydrogen facilities, including the Grangemouth site, which is Scotland's largest carbon emitter.

Industrial clusters are likely to require integration with CCUS infrastructure as a solution for processes that cannot be decarbonised by other means. This provides an obvious synergy with blue hydrogen production, where CCUS infrastructure can be shared and hydrogen can be used as an alternative to natural gas or a process feedstock.

The most advanced industrial cluster focused on blue hydrogen is the St Fergus site, which includes the Acorn CCUS and blue hydrogen production projects. However, current and previous hydrogen production and CCUS projects have been investigated in the Shetland Energy Hub and Caledonia Clean Energy Project (Grangemouth).

Scotland's **urban centres** have different challenges to rural areas. They are well connected to national energy infrastructure but have more limited access to resources in proximity. Their dense population allows for economies of scale in creation of demand and makes investment in new infrastructure more feasible. In cities, improvement in air quality becomes a significant driver in policy decisions as value is achieved not just in decarbonisation but health benefits.

An example opportunity is the switch to hydrogen for public sector fleets within a city, where a scalable demand can be created, and investment in refuelling infrastructure becomes more viable as utilisation is higher. Injection of hydrogen or full conversion of the gas networks, to provide domestic and commercial heating, would present a significant scale of demand to justify investment in production at scale.

One such example is Aberdeen's commitment to demonstrating and developing hydrogen, especially within transport. Since 2014, the original fleet of 10 hydrogen buses has stimulated the uptake of 64 smaller hydrogen vehicles into operation. A further 15 buses are due to arrive in 2020, with an additional 10 hydrogen buses being added to the fleet in 2021. The longer term vision includes deployment in a wider range of sectors including heat, rail and marine. They are also looking to increase supply of green hydrogen in addition to connectivity with the Acorn blue hydrogen project (see Hydrogen Coast case study for more details). Glasgow and Dundee have similar ambitions with early focus on decarbonisation of public sector vehicles.

This combined approach of island, urban and industrial cluster projects, provides the building blocks towards development of a hydrogen economy. Over time production and demand will increase and it is anticipated that the infrastructure associated with disparate regions will become increasingly integrated. This is reflected in long term visions of deployment, such as the Hydrogen Coast[19], where industrial and rural projects are expected to grow and integrate to increasingly serve urban centres.

HYDROGEN COAST CASE STUDY

The Hydrogen Coast is a concept which aims to work with a cluster of projects that are delivering innovative hydrogen solutions along the east coast of Scotland. It is bringing together hydrogen projects to demonstrate full transition to the hydrogen economy, encompassing both blue and green hydrogen options.

The programme is being led by Scotia Gas Networks (SGN), National Grid and Pale Blue Dot along with the partners of the hydrogen projects that are already underway across the east coast of Scotland:

- Acorn Hydrogen and Acorn CCUS – A blue hydrogen production plant producing hydrogen from natural gas landed at St Fergus, coupled with a CCUS facility that will capture the CO_2 from hydrogen production, as well as other sources, and transport it for storage in the North Sea.
- HyStorPor – Investigating the requirements for the geological storage of hydrogen. This work will support the development of hydrogen storage for Acorn Hydrogen and other Hydrogen Coast projects.
- Aberdeen Vision Project – Using hydrogen from the Acorn Hydrogen project to support decarbonisation of the national and Aberdeenshire gas transmission systems. Phase 1 proposes all gas leaving St Fergus would be injected with 2% hydrogen. Phase 2 aims to inject up to 20% hydrogen into the gas supply for Aberdeen and the Aberdeenshire region. Phase 3 aims to operate the low pressure network on 100% hydrogen.
- H100 – SGN are developing the first 100% hydrogen domestic network, in Fife. This project is building an evidence base for domestic hydrogen use and will facilitate larger trials such as that proposed in the Phase 3 of the Aberdeen Vision Project.

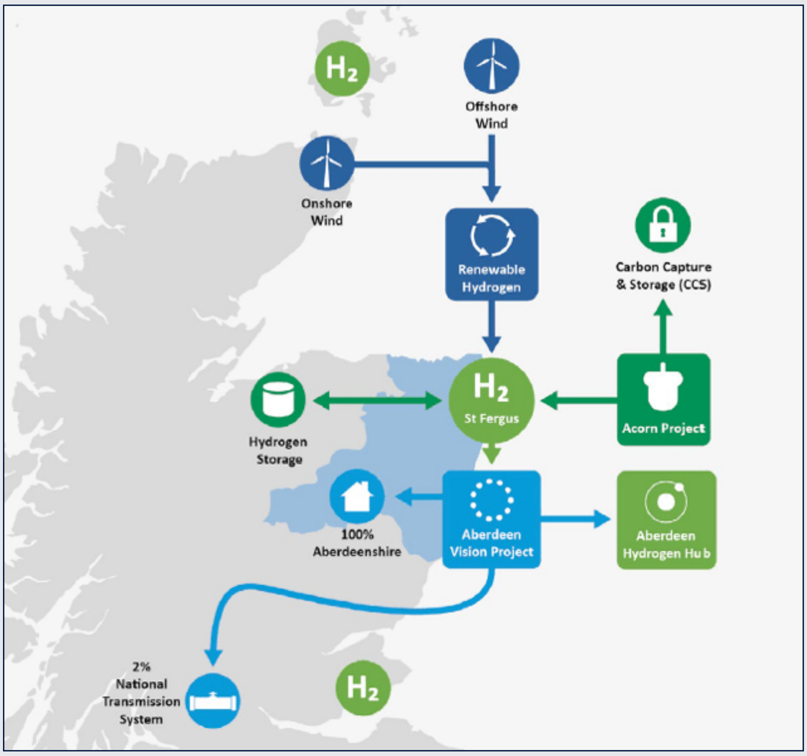


Figure 13: Hydrogen Coast overview (© Pale Blue Dot)[19]

- Aberdeen Hydrogen Bus Project – Currently operating a fleet of buses in Aberdeen powered by green hydrogen.
- The Hydrogen Hub, Aberdeen - Aims to secure a resilient and cost effective supply of green hydrogen, initially for a fleet of road vehicles, in support of the Hydrogen Bus Project and other fleet vehicles. Subsequent project phases are looking to supply marine and rail customers with green hydrogen.
- Dolphyn ERM - is exploring the possibility of using deepwater floating offshore wind assets to produce hydrogen at sea and then pipe it to shore using existing O&G infrastructure[20]. Supplying additional hydrogen into the Hydrogen Coast projects.
- Dundee Bus Project – introducing hydrogen buses to Dundee. This project provides an additional hydrogen demand along the east coast.
- Several projects in Orkney, see Orkney case study.

ORKNEY CASE STUDY

Orkney's existing and developing projects demonstrate an island approach to growing a hydrogen economy, in building block stages.

The initial Surf 'n' Turf project delivered a 500 kilowatt (kW) green hydrogen production facility on the Isle of Eday. The hydrogen is produced using tidal power from deployed turbines at the European Marine Energy Centre (EMEC), along with 900 kW community wind generation. The hydrogen is stored and transported to Kirkwall harbour, where it is used by a fuel cell to provide electricity to docked ships in the port.

Following this, the Building Innovative Green Hydrogen Island Territories (BIG HIT) project expanded on the idea of whole energy system thinking, at a local level. It aims to demonstrate that the approach can be replicated at other rural locations. Green hydrogen is produced by electrolysers on Eday (0.5 megawatt (MW)) and Shapinsay (1 MW), supplied by onshore wind, and is then stored in tube trailers for transportation to mainland Orkney. Launched in 2018 when fully commissioned 50 tn of hydrogen will be produced annually for local buildings and transported to Kirkwall for heat and power of harbour buildings, the marina, vessels and a refuelling station for road vehicles.

From these projects, numerous others have grown and are demonstrating hydrogen demand in ferries (HySeas III[21], HyDIME[22]), aviation (HyFlyer[23]) and distilleries (HySpirits[24]). The Hydrogen Offshore Project[25] on Flotta Island is also considering incorporation of O&G infrastructure. Wider energy system integration is being explored through ReFlex[26] which is exploring the potential of both hydrogen and increased electrification alongside smart management of the system to bring more renewable energy online.

Figure 14: BIG HIT island schematic (© BIG HIT)[27]

4.

HYDROGEN TECHOLOGY

4 HYDROGEN TECHOLOGY

4.1 HYDROGEN SOLUTIONS

Hydrogen has broad applications across the energy system with numerous ways to produce, move, store and use hydrogen. These are described in more detail, including their technology maturity, in Appendix A2.2.

The global energy system has always been, and will likely continue to be, multi-vector i.e. energy is produced and supplied in a diversity of ways dominated by molecules and electrons. An over reliance on any one energy vector is likely to reduce the overall system resilience.

Understanding the mix of technologies deployed in a future net-zero energy system is complex and it is likely that a range of solutions will exist which are dependent on location specific applications. A range of factors to consider are summarised in Table 4 and discussed in the context of hydrogen solutions below

> *"Hydrogen technology is already a well-established vector globally"*
>
> Stakeholder questionnaire opinion

TECHNOLOGY MATURITY/ READINESS AND RISK	Hydrogen technologies are at various stages of maturity across different applications. In the hydrogen supply chain, some technology applications are well proven and already used extensively, like SMR without CCUS. Others are still in the demonstration phase, for example fuel cell use in heavy goods vehicles and rail.
USER REQUIREMENTS, CONSUMER CHOICE AND CONSUMER ACCEPTANCE	Whether consumers accept and want to use hydrogen, will be key to how much it is used in the economy. One key advantage of hydrogen is that, as a gas, it often gives a similar user experience to the hydrocarbons solutions it will displace. For example, hydrogen fuel cell vehicle refuelling is more similar to diesel/petrol vehicles, than electrical vehicles that require much longer charging durations.
COMMERCIAL COMPETITIVENESS, COST BASE AND WHOLE SYSTEM ANALYSIS	The commercial competitiveness of hydrogen relative to the hydrocarbons they are displacing and alternative decarbonisation methods will determine the extent of hydrogen's role in the energy system. Understanding the best decarbonisation solution for an application is complex and requires an understanding of the location specific attributes of those applications, the cost trajectories of energy commodities and carbon, and the context of the impact on the wider system. Hydrogen is likely to confer benefits when considered in a wider system analysis. It provides more overall system flexibility, storage capacity and better utilisation of existing infrastructure.

Table 03: Factors influencing technology deployment in a net-zero energy system

INVESTMENT CASE	The investment case for any infrastructure project considers lifecycle cost (CapEx and OpEx), revenue/income, pay back periods and market risk. Currently decarbonisation solutions, including hydrogen, are generally not cost competitive with hydrocarbon alternatives. Until the market matures and cost reductions are realised market support/subsidy is likely to be critical to support hydrogen business models.
SOCIO-ECONOMIC BENEFIT	A Just Transition is not just about focusing on delivery of the lowest cost decarbonisation solution. It also needs consideration of the creation of jobs and economic benefits associated with the transition. Net-zero will result in a major shift away from a carbon based economy into a new green economy, requiring different skills and economic activities. Early movers in hydrogen are likely to capture more economic benefits by securing these new activities. However, it is important to be realistic and focused on where economic value can be captured, considering indigenous strength relative to global capability and the scale of the domestic industry.
GEOGRAPHY	Geography has a key role to play in how any hydrogen economy will develop, and it is possible that solutions will be region and location specific. The cost of hydrogen at point of demand depends on the local cost base of production, the way in which it is distributed and stored, as well as the cost base of the energy source it is displacing. Rural and island locations often have high fuel costs and local constrained renewable production which provide economically favourable conditions for hydrogen as a solution. Urban centres are generally not co-located next to production, but do have more developed existing infrastructure, and larger volumes of demand to stimulate hydrogen production at scale.

Table 03: Factors influencing technology deployment in a net-zero energy system (continued)

4.2 HYDROGEN ENERGY COSTS

PRODUCTION COSTS

Some hydrogen technologies are mature with established costs, others are relatively novel and therefore offer significant opportunities for cost reduction. As the use of hydrogen increases, economies of scale offer an opportunity to decrease the unit cost and therefore the price of hydrogen delivered to applications.

Currently hydrogen production costs vary significantly based on the production method and production location. Multiple recent international studies have attempted to estimate how both blue and green hydrogen production cost will evolve globally out to 2050. The uncertainty of how these costs will evolve means that estimates can vary substantially.

This is particularly true for green hydrogen production, as it is less mature and reliant on renewable electricity costs, which itself has a wide cost range. Most studies conclude that blue hydrogen will have a lower cost over the next decade or so, with green hydrogen potentially competing with blue from the mid-2030s onwards.

> *"The challenge now is more about commercial and market readiness levels as opposed to technology readiness"*
>
> Stakeholder questionnaire opinion

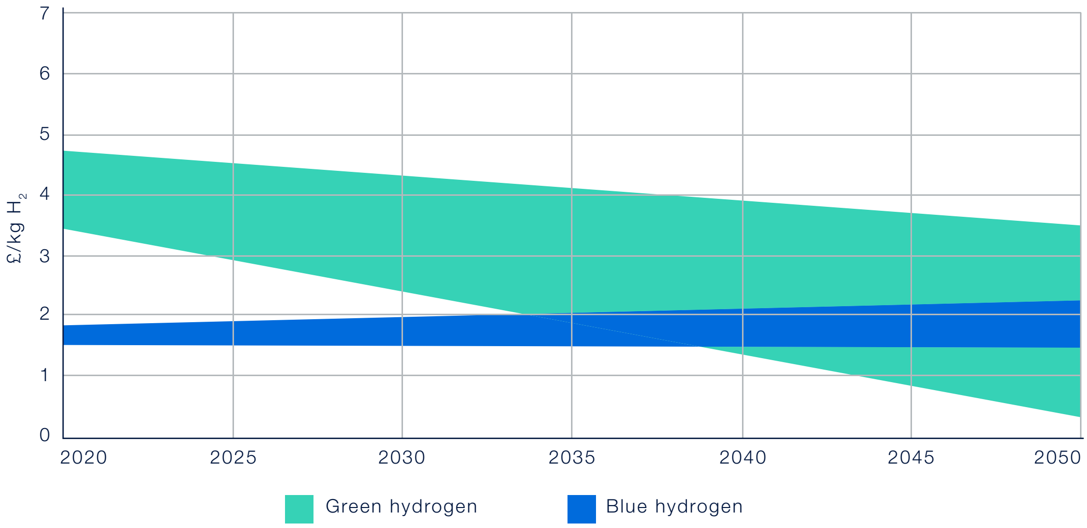


Figure 15: Cost estimates of blue and green hydrogen production costs out to 2050 [28, 29, 30, 31, 13, 32, 33, 34, 35]

Blue hydrogen costs are essentially the wholesale natural gas price plus a production 'premium'. This covers the efficiency loss (i.e. the additional kilowatt hour (kWh) of natural gas required for each kWh of hydrogen produced) the cost of transporting and storing the carbon and the operational and capital costs of the plant itself. Blue costs are expected to increase out to 2050 as the cost of natural gas rises and potential carbon taxes are introduced.

To limit the need to construct additional natural gas pipelines, blue hydrogen production will need to be near large natural gas sources or import points.

It will also need to be in proximity to CCUS facilities, or at least be connected to any future CCUS networks.

Green hydrogen costs are also mostly determined by the feedstock costs, in this case renewable electricity. Costs also include the capital expenditure CapEx and operational expenditure OpEx and efficiency of the electrolyser system.

The reducing cost of renewable electricity, increased scale of electrolyser manufacture and improved efficiencies mean that the cost of green hydrogen is expected to reduce substantially out to 2050.

Figure 16 shows impacts of electricity price on hydrogen production costs in 2035 shows how significantly green hydrogen production is impacted by electricity price. Using today's electricity price with a forecast CapEx and OpEx for 2035 results in a hydrogen cost of over £3/kilogram (kg), with the feedstock electricity accounting for over 70% of the total hydrogen cost. This is compared to a hydrogen cost of under £2/kg if the electricity can be sourced at 2p/kWh. For Scotland, driving down the cost of offshore and onshore wind electricity production, will be key to cost effective green hydrogen production.

Figure 16: Impacts of electricity price on hydrogen production costs in 2035

HYDROGEN TRANSPORTATION AND STORAGE COSTS

Transmission and distribution

Production costs are only part of the story, the costs of transporting the hydrogen from production to end usage application is important for determining the overall costs. Currently, most hydrogen production is co-located with end use. In the future this will not be practical for all end uses.

It is expected that transmission and distribution pipelines will be the lowest cost option in moving hydrogen from production source to end user. The capital costs of building new transmission pipelines or a new distribution network is a significant investment and would require substantial volumes for it to be viable. However, if the existing network could be converted then much of these costs could be avoided.

Scotland's gas transmission and distribution system could be converted to accept hydrogen, either as a blend or as full hydrogen networks. Larger interconnector pipelines could be used to connect Scotland to Europe.

Hydrogen can also be transported using road or rail either as a gas, liquid or as ammonia and all are mature technologies in use today. However, due to its low volumetric energy density there is less energy moved per vehicle, requiring more delivery vehicles on the road to meet demand.

Additional shipping and port facilities, such as liquefaction plant and hydrogen storage, would be required to facilitate the export of hydrogen from Scotland. There are several ports in Scotland that could be repurposed to support the export of hydrogen, in the form of shipped liquid hydrogen or ammonia produced from hydrogen.

Figure 17: Common hydrogen transportation methods

The potential to use the existing gas network is one of the main attractions for using hydrogen in Scotland and the UK, which has a relatively well-developed gas network compared to many other countries.

Transporting gas overland by rail or lorry results in significantly higher operational cost than pipelines, but offers much more flexibility supplying smaller users where the capital expense of pipelines would not be justified[36, 37]. All transportation technologies are described in more detail in Appendix A2.2.

Storage

As a gas, hydrogen offers significant advantages over electricity when it comes to storage, particularly long term seasonal storage between summer and winter. Figure 18 provides a summary of the different hydrogen storage options.

Storing hydrogen does pose additional challenges compared to natural gas due to its relatively low energy density. It is estimated that if hydrogen were to completely replace natural gas in the world economy today, total storage infrastructure would need to increase 3-4 times[13].

Compressed gas hydrogen storage is more expensive than storing hydrogen in a salt cavern or other underground facilities on a per kilogram basis. However, the very high upfront cost of underground storage means that it is only available once hydrogen production has reached sufficient scale to warrant such an investment. Liquified hydrogen storage has higher capital and operational costs than compressed hydrogen but it is used when space is a key concern e.g. to transport hydrogen.

All storage technologies are described in more detail in Appendix A2.2.

COMPRESSED GAS IN PIPELINE TRANSMISSION SYSTEMS

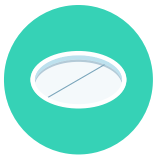
Allows for the storage of daily and weekly variations in the gas network. Linepacking is not as effective for hydrogen as it is for natural gas due to hydrogen's lower density.

HIGHLY COMPRESSED GAS IN PRESSURISED CONTAINER VESSELS

Hydrogen's low density means high pressures are required to store large amounts of energy. Compression allows the storage of hydrogen in smaller volumes, and is appropriate for small scale, short term storage like that used for hydrogen refuelling stations. This type of storage could be used in a modular way to reach much larger quantities but this is expensive.

LIQUID IN COOLED PRESSURISED VESSELS

Liquification costs energy and hence is a more expensive storage medium. It allows far greater energy densities to be reached and is likely to be used either where space is a premium or for longer distance transport.



LARGE UNDERGROUND STORAGE FACILITIES

Geological storage solutions benefit from high capacity and therefore low unit costs. However, it requires significant volumes of produced hydrogen to make the initial investment. Within Scotland, the key opportunity for this form of storage is through the reuse of old O&G infrastructure both onshore and offshore.

Figure 18: Common hydrogen storage options

Conversion to ammonia

Ammonia offers a potential option for both transporting and storing hydrogen. Ammonia has a much higher energy density than gaseous or liquid hydrogen, which may make it an attractive mechanism for both transporting and storing hydrogen. There is already a large worldwide market for ammonia, and it is regularly transported in large quantities[37]. However, this needs to be balanced against the additional cost, energy requirements and any associated emissions from the conversion of hydrogen to ammonia, and reconversion back to hydrogen at the point of use[37].

4.3 HYDROGEN SUPPLY AND DEMAND BALANCE

SCOTLAND'S ENERGY DEMAND

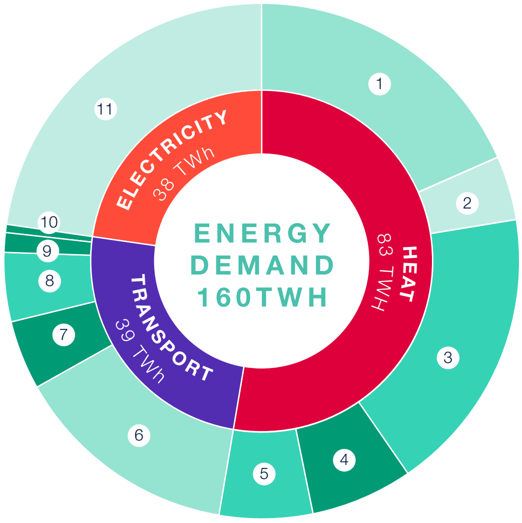
Scotland's current energy demand equates to approximately 160 TWh[38], circa 10% of the UK's total energy demand of 1,640 TWh[39]. The Scottish Energy Strategy[40] estimates that total energy demand by 2050 will decrease by 5-28%, to 110 TWh – 148 TWh[40].

A breakdown of Scotland's energy demand by sector is shown in Figure 19. These are ranked in terms of likelihood to transition to hydrogen based on stakeholder feedback as discussed in Section 5. The darkest green represents areas most likely to transition to hydrogen, and lightest green most likely to be decarbonised by other means.

This gives an indication of the sectors that could be supported to grow early hydrogen demand, even if their overall contribution to energy demand is small. For example, a transition within rail and buses to hydrogen can be an early route to creating demand. However, by 2045, the total amount of hydrogen used in those sectors makes them a small overall contributor.

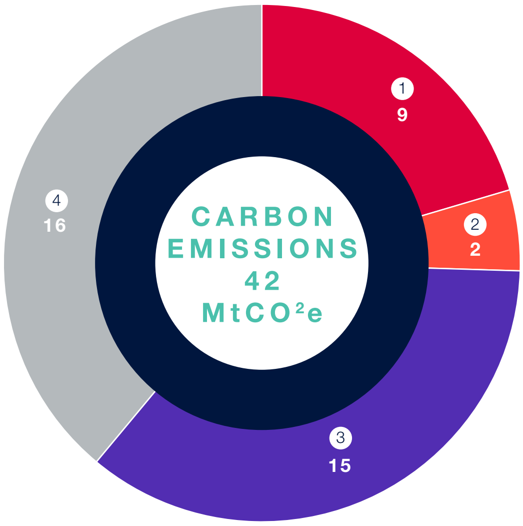
The carbon emissions from these sectors shown in Figure 20, provides a view of the relative carbon intensity of each sector. Heating makes up for over 50% of Scotland's energy demand, but only accounts for approximately 20% of carbon dioxide emissions. Transport accounts for approximately 25% of energy but generates over 35% of all carbon emissions. As such decarbonising relatively smaller proportions of our transport demands, will provide much more benefit in terms of reducing carbon emissions.

> *"Supply of hydrogen and demand must happen together and this can be challenging without coordination"*
>
> Stakeholder questionnaire opinion



1. Commercial and industrial non-gas
2. Domestic non-gas
3. Domestic gas
4. Industrial gas
5. Commercial gas
6. Diesel and petrol cars
7. Heavy goods vehicles (HGV)
8. Diesel light goods vehicles (LGV)
9. Buses
10. Rail
11. Electricity

Figure 19: Scotland's energy demand in 2017, excluding aviation or water transport[41]



1. Heat
2. Electricty
3. Transport
4. Others

Figure 20: Scotland's carbon emissions in 2018[42]

HYDROGEN PRODUCTION POTENTIAL

Scotland has the potential to produce significant quantities of both green and blue hydrogen. An ambitious view of Scotland in the next 20 years could see the country becoming an exporter of hydrogen to the rest of Europe. However, this is dependent on market conditions and ability to realise cost reductions.

Comparing blue and green hydrogen production

A blue hydrogen production plant rated at 1 GW will produce significantly more than a 1 GW green hydrogen production plant. Electrolysers quote their maximum energy capacity at the input of the electrolyer and SMR/ATR quote a value at the output of the SMR/ATR.

A 1 GW offshore windfarm, operating at a 58% capacity factor connected to a 1 GW electrolyser with an electrolyser conversion efficiency of 69% would produce 3.5 TWh of green hydrogen (92,000 tn) from the 5.1 TWh of input electrical energy.

A 1 GW blue hydrogen production facility operating with a capacity factor of 86% and a conversion efficiency of 80% would produce around 7.5 TWh (225,000 tn) of hydrogen in a year. This requires around 9.75 TWh of natural gas.

Appendix A2.1 provides more detail.

Green hydrogen production

There are two key factors that limit the potential for growth of green hydrogen production in Scotland: renewable energy generation capacity and green hydrogen plant/electrolyser build out potential. While the former is more directly influenced by UK and Scottish government policy, the latter is likely to be strongly influenced by what happens in a global market.

It is unlikely that renewable electricity resources will be the limiting factor in green hydrogen production, given the scale of potential resource and maturity of the market. It is more likely that the scale up and practical build out rates of green hydrogen production plant/electrolysers, will dictate the installed capacity of green hydrogen production achieved by 2045.

The most ambitious scenario in this assessment assumes that Scotland could credibly reach an installed capacity of 5 GW by 2032 and over 35 GW by 2045. This assumes strong global market support for hydrogen production which stimulates the supply chain.

Renewable energy potential

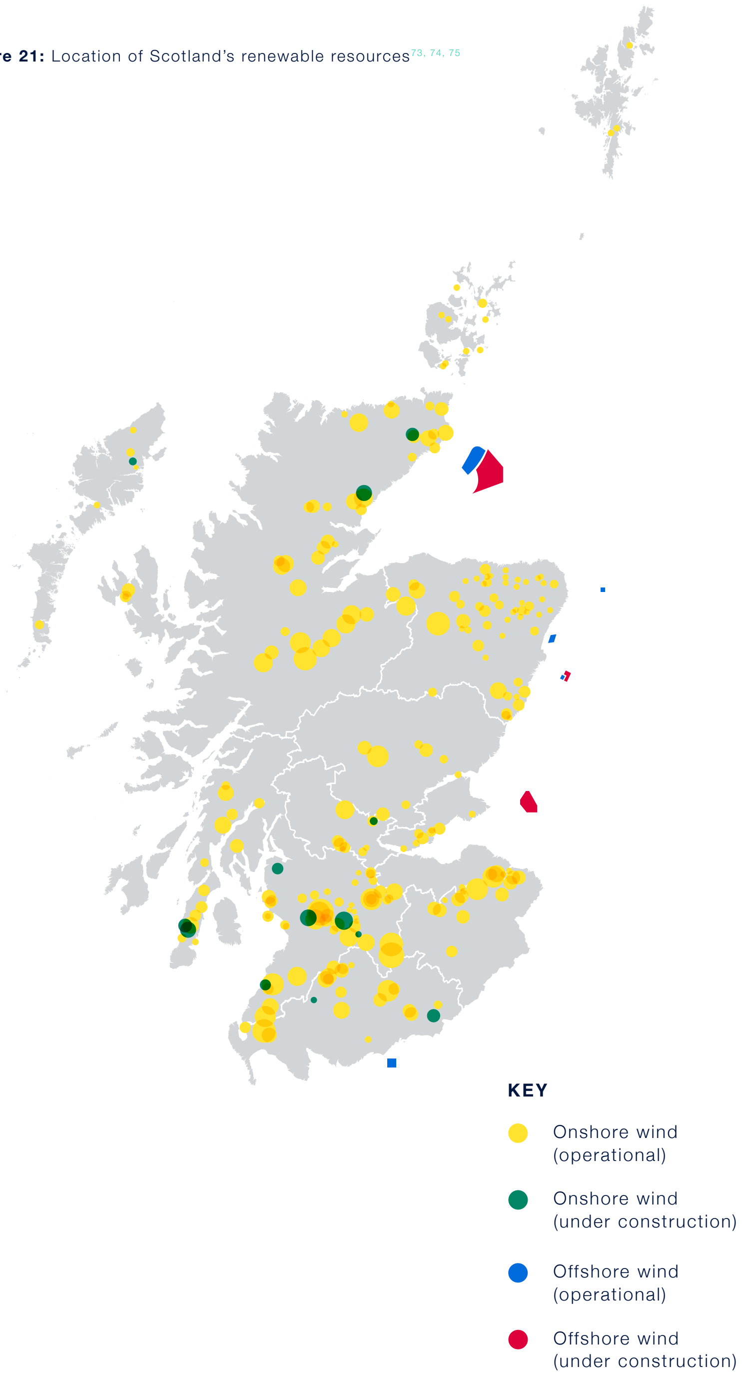
Scotland has some of the world's best renewable energy resources including 25% of Europe's offshore wind resource, extensive wave and tidal resources and over 60% of the UK's onshore wind capacity[43].

In a supportive planning and fiscal regime approximately 800 MW/year of renewable electricity was installed over the last decade to reach a total installed capacity of 11.9 GW, the vast majority of which is onshore wind[44]. The newer and fast growing offshore wind industry now has just under 1 GW of installed capacity[45].

The ultimate potential for renewable energy capacity in Scotland is difficult to estimate, as theoretical potential is limited by what is environmentally and commercially viable, as well as practical build out rates. However, the ultimate potential in Scotland is considered likely to be significantly larger than Scotland's and even the UK's indigenous demands[46].

It is likely that offshore wind will grow to take an increasingly larger proportion of new build capacity. The CCC have estimated that the UK may require up to 75 GW of offshore wind by 2050 to meet UK demands, reaching build out rates of up to 4 GW/annum[4]. In Scotland there is 8.4 GW of onshore wind in planning or construction, compared to 7.5 GW of leased offshore wind in the pipeline[47,48]. A further 10 GW of offshore wind is anticipated to be leased through Crown Estate Scotland's ScotWind leasing round. Longer term, wave and tidal have the potential to contribute to installed capacity and the Offshore Renewable Energy Catapult predict that in the UK as a whole 1 GW of tidal energy could be installed by 2030, and 1 GW of wave energy by 2040[49]. However, there is limited visibility in the pipeline of renewable projects beyond 2030.

Figure 21: Location of Scotland's renewable resources[73, 74, 75]



Hydrogen may help unlock renewable energy resources that previously were not economically viable by offering a more diverse route to market and alternative revenue streams, by better use of existing infrastructure, and by separating production locations from demand locations.

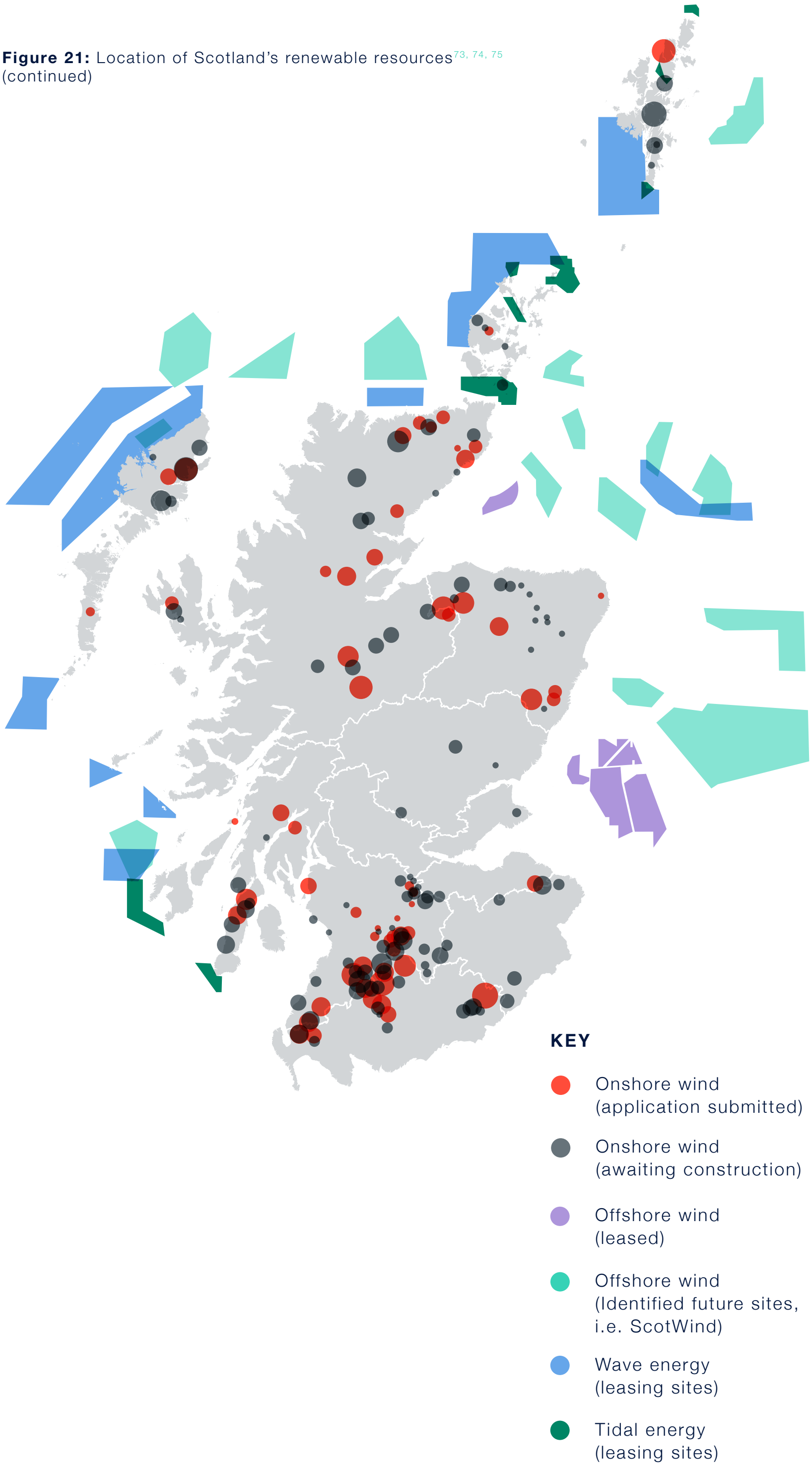
For onshore wind, wave and tidal this could include development in areas of grid constraint, improving system flexibility and management of local supply and demand. For offshore wind, integration with O&G infrastructure could improve project economics. Hydrogen has the potential to play a critical role in supporting a Scottish offshore wind market as Scotland's challenging technical conditions and unfavourable grid charging regimes have resulted in Scottish projects being at a disadvantage to projects in the rest of the UK.

The assumed maximum build out rates of green hydrogen production of 5 GW by 2032 and 35 GW by 2045, are not likely to exceed what could be theoretically constructed in Scotland given the right market conditions.

The locations of Scotland's renewable resources are shown below. Scotland's existing offshore wind projects are largely clustered in the Firth of Forth and the Moray Firth off Scotland's east coast. However, ScotWind leasing rounds and the wave and tidal resources are more widely distributed round the Scottish coastline. Significant renewable potential is held in the islands and rural areas, including the Western Isles, Orkney and Shetland, that are grid constrained.

These resources could be used to produce electricity and/or hydrogen at point of generation or support centralised production of hydrogen onshore. Optimising the system economics and driving down the costs of green electricity production will be critical, as electricity cost constitutes a large percentage of the end cost of hydrogen.

Figure 21: Location of Scotland's renewable resources[73, 74, 75] (continued)



Green hydrogen plant potential

Green hydrogen plant/electrolyser build out rates are likely to be the main constraint for scale up of green hydrogen production.

There are practical constraints in how quickly a market is likely to scale up, due to supply chain capacity constraints and investment market confidence. In order to secure investment in multi GW projects, the supply chain will need to ramp up capacity, and investors will need to be comfortable with the technology and market risks. These are likely to progress in parallel, if a market demand is established, then secured orders will allow cost reductions in technology to be achieved, investors will become more comfortable with risk and the projects can grow in scale.

However, this pathway is dependent on reducing the cost of renewable electricity in the Scottish market, which will strongly influence the production costs of hydrogen. It is also highly reliant on the global market stimulating demand for hydrogen production systems, as optimal cost reductions are unlikely to be achieved through supply of a Scottish market in isolation.

The rate of growth of the green hydrogen production market, is highly influenced by the strength and consistency of the market support. The UK offshore wind market grew from sub 100 MW projects around the turn of the century, to installing approximately 800 MW per year in cumulative capacity in just over a decade[50]. This was enabled by relatively stable market support regimes.

Currently the global electrolyser market is relatively small and the largest electrolyser systems that are being built are around 10 MW scale. Scotland has a modest pipeline of identified green hydrogen production projects. Figure 22 shows how the potential green hydrogen production capacity could be built up around Scotland.

BY 2025

Individual electrolyser systems should reach 100 MW scale, through projects such as ITM Power's Gigastack. The scenarios in this assessment assume that in optimal market conditions, with the appropriate incentives in place, multiple small to medium scale projects could be deployed in Scotland within the 2025 timescale. This could result in 100s of MWs of installed capacity.

BY 2032

Germany's ambition is to reach 5 GW of installed capacity by 2030. It is assumed that Scotland could credibly match this level of ambition by 2032, assuming that within a decade the installed capacity of projects have reached circa 800 MW per year. This is comparable to the growth rate of the UK offshore wind sector.

2032 TO 2045

The assessment scenarios assume that the most optimistic outcome is a strong UK and European demand for hydrogen. This also assumes stable market support, strong supply chain growth and cost reduction are achieved resulting in multi GW installed capacity projects and a total installed capacity of 37 GW.

Figure 22: Assumed maximum green hydrogen production scale up[51]

Blue hydrogen production

There are a number of factors that potentially limit the growth of blue hydrogen production in Scotland. Similar to green production, access to feedstock, in this case natural gas, and practical build out rates of blue hydrogen production plant are key. Moreover, matching supply to demand, investment periods, compatibility with carbon targets and competition with green hydrogen production have an impact.

While increasing blue energy production will create an increasing reliance on natural gas imports, this is not considered to be a constraint. It is considered more likely that the scale up of supply will be matched to meet indigenous demand, but not an export market. This will ultimately be curtailed when green hydrogen cost reductions mean the price of green drops below the price of blue (given that the latter is not zero carbon).

The most ambitious scenarios in this assessment assume that Scotland could credibly reach an installed capacity of 200 MW by 2025, 2 GW by 2032 and 5 GW by 2045.

Supply of natural gas potential

Natural gas is the feedstock of blue hydrogen production and so securing a supply is critical to investment in blue hydrogen production.

Scotland plays a key role in the supply of natural gas to the wider UK system, both from its indigenous production, but also as an importer from the wider North Sea gas network. The total flow of gas through St Fergus, both imports and indigenous, varies on an annual basis, and in 2019 was approximately 240 TWh, almost four times Scotland's current natural gas demand.

However, the UK Continental Shelf (UKCS) is an ageing basin and the total production of natural gas is in decline. Predicting the remaining economically viable reserves in the North Sea is challenging. It is possible that a hydrogen market, and more integration of offshore renewables with O&G assets, would increase the economic viability of reserves and slow the decline, thereby increasing overall production. The UK Government's 'Maximising Economic Recovery' strategy[52] seeks to slow the decline. However, Oil & Gas UK predict that by 2045, UK production will be approximately 30% of 2020 production[53].

The majority of the UK's natural gas supply already does not come from indigenous supply. In 2018 the UK imported 54% of its total natural gas demand from global markets[54]. The proportion of UK gas imports will increase over time, if reliance on gas does not reduce as indigenous reserves declines.

The 'Further Ambition' scenario from CCC's Net Zero Technical report[3], assumes that up to 225 TWh of blue hydrogen could be required to achieve net-zero targets, but also assumes that it is achieved through increasing natural gas imports. It is therefore likely that blue hydrogen production at scale, will not be limited by availability of natural gas feedstock, but will result in an increasing reliance on imports.

Blue hydrogen plant potential

The Further Ambition scenario from CCC's Net Zero Technical report[3], assumes that up to 30 GW of methane reformation capacity will be constructed in the UK by 2050, assuming build out rates grow to 2-3 GW per year.

In Scotland scale up of blue hydrogen is likely to be demand driven, rather than supply driven. As blue hydrogen is not zero carbon and produces a lower purity hydrogen, compared to green production, it is unlikely that there will be an export market. This is supported by recent German and EU commitments to secure a green hydrogen network.

Blue hydrogen is therefore likely to be limited to use within the domestic gas network, or to meet local industrial demands. This is the logic of early blue hydrogen production projects like Acorn, which will see 200 MW of production installed in around 2025 to match 2% injection into the national gas transmission network[55]. Figure 23 shows how the potential blue hydrogen production capacity could be built up around Scotland.

4.4 INNOVATION AND ACADEMIA

Scotland, the UK and the EU have complex structures of support for the development and innovation of energy technologies, from early stage fundamental research, right through to commercialisation.

A number of Scottish organisations are already taking a supporting role in the hydrogen economy, focusing on various stages of development. These include partnerships between industry, academia and public sector such as NECCUS[56], focused on supporting blue hydrogen through CCUS, and DeepWind[57], supporting green hydrogen through offshore renewables. However, there remains limited support for funding or partnerships focused wholly on hydrogen.

BY 2025

Project Acorn comes online. This 200 MW blue production facility is the only one in Scotland at this point.

BY 2032

An additional 2 GW of blue hydrogen production could be added. The limiting factor is likely to be the demands that the blue production facilities will meet.

2032 TO 2045

Approaching 2045, blue hydrogen build out rate slows. This now becomes limited by investment decisions due to the reductions in green hydrogen costs.

Figure 23: Assumed maximum blue hydrogen production scale up

Scotland's universities have long played a role in supporting the national energy industry. Research and development (R&D) conducted in universities has a key role in developing innovative solutions and enabling technology development. Scotland's academic institutions are currently conducting some world leading academic work on hydrogen, such as HyStorPor[58]. This research is funded from a wide range of Scottish, UK and European funds.

The newly launched Hydrogen Accelerator will seek to draw on collaborations between universities, public sector and industry to support the early development of technologies and other hydrogen solutions in the transport sector[59]. Figure 24 shows Scotland's key academic skills and strengths in the hydrogen sector. More detail on this is available in Appendix A2.3.

		TECHNOLOGY READINESS LEVEL						
UNIVERSITY	**HIGHLIGHTS**	Hydrogen Production	Hydrogen Transportation and Storage	Hydrogen Demand	Whole System Modelling	Economic Modelling	Policy Development	Skills Development
University of Edinburgh	Larger fund focusing on hydrogen only including €5M BIG HIT, €6.99M HyTransit (Aberdeen Bus Project)		■		■			
University of St Andrews	Larger fund including €1.64M HyTrEc, €600k The Hydrogen Office			■		■	■	
Heriot-Watt University	Industrial Decarbonisation Research and Innovation Centre - Accelerate industrial decarbonisation of 6 major industrial clusters	■		■		■	■	
University of Strathclyde	Centre for Energy Policy - Research, knowledge exchange and policy stakeholder engagement hub	■		■	■	■	■	
University of Glasgow	Next generation electrolysis - Innovations in electrolyser chemistry to improve efficiency	■						
University of the Highlands and Islands	Hydrogen skills laboratory - Developing technical skills for a hydrogen conversion			■				■
Edinburgh Napier University	Scottish Energy Centre - Supporting the development of renewable energy systems in construction			■	■			
University of Aberdeen	Aberdeen Schools Challenge - Working with local hydrogen projects to drive learning from early ages							■
Robert Gordon University	Hydrogen Vehicle Fleet - Working with local hydrogen projects through operation of hydrogen vehicles			■			■	

Figure 24: Summary of Scotland's academic strengths and skills

Figure 25 and Figure 26 provide a summary of some of the key funding opportunities and partnerships for hydrogen and where on the innovation spectrum these are targeted.

Despite the current focus, there is no overarching organisation that is co-ordinating the Scottish or UK research and innovation efforts focused on hydrogen. There are particular challenges in bringing together elements of funding that can support end to end projects that include production, distribution and demand. Targeting innovation funding on areas that align with Scotland's skills and supply chain can help capture more economic benefits.

Scotland could benefit from a strategic focus on where interventions in supporting innovation should be focused to best leverage benefits across the hydrogen value chain.

Engagement with industry suggested a desire to create an organisation which would co-ordinate innovation in a similar way to the role of the Catapults, Oil and Gas Technology Centre (OGTC), and H2FC Supergen.

KEY

- Multi-vector
- Transport

TECHNOLOGY READINESS LEVEL

Organisations that only support direct hydrogen projects highlighted green

ORGANISATION	HIGHLIGHTS	Early stage R&D e.g. lab scale			Early small scale Demonstration			Full scale demonstration and commercial roll out		
		1	2	3	4	5	6	7	8	9
SCOTLAND										
Hydrogen Accelerator	£300k - transport focussed hydrogen projects	Multi-vector	Multi-vector	Multi-vector	Multi-vector					
Energy Technology Partnership			Multi-vector	Multi-vector	Multi-vector	Multi-vector				
Scottish Energy Laboratory				Multi-vector	Multi-vector	Multi-vector	Multi-vector			
Scottish Carbon Capture and Storage				Multi-vector	Multi-vector	Multi-vector	Multi-vector			
Energy Transition Fund	£62M total - support O&G and energy sectors including hydrogen				Multi-vector	Multi-vector	Multi-vector			
Local Energy Challenge Fund	£20M total - including £4.7M Levenmouth Community Energy Project, £1.1M Surf 'n' Turf						Multi-vector	Multi-vector		
Low Carbon Infrastructure Transition Programme	Larger fund including £100k H100 Feasibility Study							Multi-vector	Multi-vector	
DeepWind									Multi-vector	Multi-vector
NECCUS									Multi-vector	Multi-vector
Ultra-Low Emission Bus Scheme	£9M total - supporting electric and hydrogen buses								Transport	Transport

Figure 25: Key funding and partnership opportunities across Scotland

TECHNOLOGY READINESS LEVEL

Organisations that only support direct hydrogen projects highlighted green

ORGANISATION

Organisation	HIGHLIGHTS	Early stage R&D e.g. lab scale			Early small scale Demonstration			Full scale demonstration and commercial roll out		
		1	2	3	4	5	6	7	8	9
UNITED KINGDOM										
Natural Environment Research Council		■	■	■	■					
Engineering and Physical Sciences Research Council	H2FC Supergen research hub	■	■	■	■					
Economic and Social Research Council		■	■	■	■					
BEIS - Industrial Strategy Challenge Fund	£20M - Industrial Decarbonisation Research and Innovation Centre including support for hydrogen		■	■	■	■	■	■	■	■
Innovate UK	Provides partial support to HyFlyer Project		■	■	■	■	■			
Innovation Catapults				■	■	■	■	■		
BEIS - Hydrogen Supply Competition	£33M total fund - including support for Scottish projects £3.12M Dolphyn, £2.7M Acorn Hydrogen					■	■	■		
Oil and Gas Technology Centre								■	■	■
BEIS - Industrial Fuel Switching	£20M total fund including £5.24M HyNet North West					■	■	■		
Ofgem - Network Innovation Allowance				■	■	■	■			
BEIS - Hy4Heat	£25M total - Feasibility of hydrogen for heating			■	■	■	■	■		
Ofgem - Network Innovation Competition	Larger fund including £6.8M H21 Phase 2							■	■	■
Ofgem - Renewable Heat Incentive									■	■
Low Carbon Contracts Company - Contract for Difference									■	■
OLEV - Ultra Low Emissions Bus Scheme									■	■
Department for Transport - Road Transport Fuel Obligation										■

ORGANISATION *Organisations that only support direct hydrogen projects highlighted green*	HIGHLIGHTS	TECHNOLOGY READINESS LEVEL Early stage R&D e.g. lab scale			Early small scale Demonstration			Full scale demonstration and commercial roll out		
		1	2	3	4	5	6	7	8	9
EUROPE										
Fuel Cell and Hydrogen Joint Undertaking	Larger fund focusing on hydrogen only including €5M BigHIT, €6.99M HyTransit (Aberdeen Bus Project)									
European Regional Development Fund	Larger fund including €1.64M HyTrEc, €600k The Hydrogen Office									

Figure 26: Key funding and partnership opportunities across UK and Europe

KEY

- Multi-vector
- Industrial
- Heat
- Electricity
- Transport

5.

THE DEVELOPMENT OF HYDROGEN IN SCOTLAND

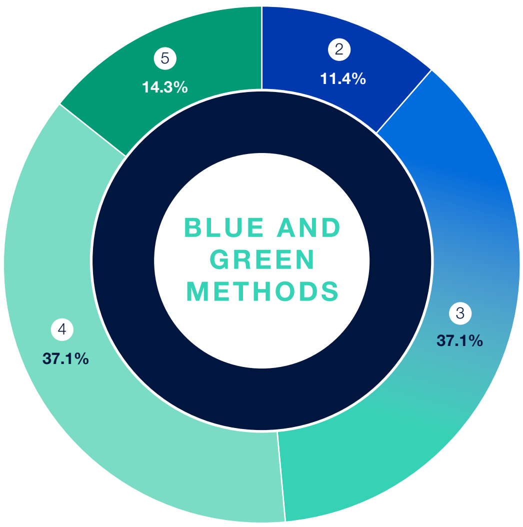
5 THE DEVELOPMENT OF HYDROGEN IN SCOTLAND

Although hydrogen has been used in some industrial applications for decades, it is in its infancy as an energy vector. It does however have the potential to significantly contribute to delivering a net-zero economy in Scotland, the UK and globally. It seems likely that hydrogen will play some role as an energy vector, what is currently uncertain is the extent of that role.

There are different options for how hydrogen will be produced, transported and used. To explore these various options, a literature review was undertaken, in conjunction with extensive stakeholder engagement with those likely to be involved in the future hydrogen sector in Scotland and further afield (see Section 1 for more on the stakeholder engagement conducted). What emerged is a varied picture with a number of different potential options for hydrogen deployment, but with some common themes.

5.1 PRODUCTION

It is generally considered that given its resources Scotland could, if there was enough demand, become a major producer of hydrogen, both blue and green. The majority of stakeholders considered that the hydrogen produced would be 'mainly green' or a 'mixture of blue and green' production.



1. Blue only (no stakeholder selected)
2. Mainly blue
3. Mixture of blue and green
4. Mainly green
5. Green only

Figure 27: Stakeholder responses to 'how hydrogen production is split between blue and green production methods.

GREEN HYDROGEN

The majority of stakeholders agreed that green hydrogen production will be an important part of Scotland's future.

Initially production is expected to be small to medium scale, up to circa 200 MW per unit, primarily using onshore wind. This production would likely be co-located or near to end users.

> *"Scotland can produce as much hydrogen as it has the ambition to produce from offshore wind using as much existing infrastructure as possible while at the same time building for the future"*
>
> Stakeholder questionnaire opinion

Numerous stakeholders raised the prospect of producing hydrogen from constrained renewable generation. For example, when grid constraints mean that a wind farm cannot export its energy to the grid at certain times, it could switch to hydrogen production. This would enable many renewable energy projects that would otherwise not be possible to be brought forward.

In the long term hydrogen production from offshore wind was believed to be the main way to achieve large scale production and is viewed by many as an exciting opportunity to unlock more of Scotland's offshore wind potential. Both offshore and onshore wind could also provide further opportunities in remote or island locations where the wind resource is particularly strong. Two production options were discussed: hydrogen produced on offshore platforms and piped to the shore, potentially avoiding the need for costly offshore electricity connections; or connected by electric cable and produced onshore, giving the operator the opportunity to produce hydrogen or supply electricity to the grid, which may have commercial and system wide benefits.

Other renewable energy resources, particularly wave and tidal, could play a role as the technologies are commercialised and scaled up particularly in remote or island locations. Green hydrogen could allow these areas to be energy independent. Some stakeholders also mentioned hydroelectric power as a potential technology for green hydrogen production.

Whether large scale green production can be viable depends on the hydrogen demand and unit cost of producing hydrogen. If demand is high enough and costs could be reduced, then many stakeholders thought that Scotland's offshore wind resources and skills are likely to be able to meet Scottish or UK demand and potentially an export market. However, it is likely that this will only be achieved through either government support mechanisms and/or clear targets to support the development in the short term. It was thought that support for green production at this early stage would accelerate deployment and enable more of the value chain to be captured in Scotland.

> *"Hydrogen provides the opportunity for parts of Scotland to become energy independent with a combination of remote demand for conventional energy (making it expensive) and natural energy resources being abundant - Highlands and islands for example. There is a constraint in terms of demand being sub-scale and sub-commercial, but the social benefits are strong"*
>
> Stakeholder questionnaire opinion

BLUE HYDROGEN

It is thought that Scotland has the skills and infrastructure, both in gas supply and potential carbon storage facilities, to enable large scale blue production. However, stakeholders were divided on the role of blue hydrogen production in Scotland with only around half the stakeholders interviewed saying that blue production should play a significant role.

If blue hydrogen is to be produced, most literature and stakeholders consider that it will be a transition fuel in the medium term. Blue hydrogen could supply relatively low cost hydrogen, in the large scales needed to enable a hydrogen economy before eventually being phased out in favour of green. However, a key uncertainty is when that transition will happen.

Given the scale needed for blue production and the investment life-time of the assets, it is thought that if blue hydrogen facilities were to be built in the next decade or so they would likely still be operational in 2045, with the phasing out in favour of green production happening later. If blue hydrogen facilities were required to close by 2045, before the end of their asset life, the unit cost of hydrogen would increase. Investors would need to recoup the significant upfront capital investment over a shorter period, unless a form of Government assistance or subsidy was provided. If this progressed, the carbon that is emitted from blue production would need to be offset in other parts of the energy system, for net-zero in 2045 to be achieved. It was thought that this offsetting could potentially be achieved by having a percentage of biogas within the methane stream.

"If we are living through a climate crisis we should be forgetting completely about blue and focussing on green"

"With the right support, by 2030 bulk hydrogen could be being produced at scale, with a key role for both blue and green hydrogen. By 2045 the role of blue hydrogen would be expected to be eclipsed by green"

Stakeholder questionnaire opinion

Another relevant factor raised by stakeholders is the purity of hydrogen. The green production process would result in high purity hydrogen of +99.9% that can be used in hydrogen fuel cells, particularly in transport applications. Blue hydrogen production gives lower purity, ~98% which can be used in combustion applications, boilers, cooker, industrial heating etc., but would need to be cleaned for use in fuel cells. It was considered that this could give rise to different grades of hydrogen, high purity green hydrogen and lower purity blue hydrogen which may have different markets and different prices.

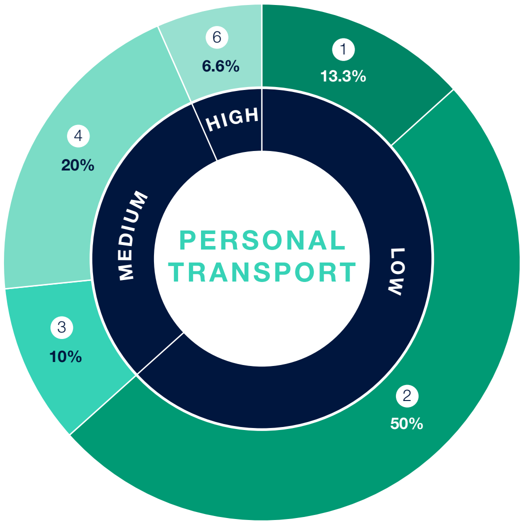
5.2 DEMAND

TRANSPORT

Both the literature and stakeholders supported the view that hydrogen was going to play some role in the transport sector. Significant commitments are being made within Scotland on both policy and implementation of hydrogen in transport. The Automotive Industry Advisory Group has been established by Transport Scotland with a strong emphasis on hydrogen. Both the Hydrogen Accelerator at St Andrew's University[60] and the Michelin Scotland Innovation Parc[61] are centred on hydrogen as a part of sustainable mobility.

Larger, heavier vehicles were consistently identified as particularly suited to hydrogen. This includes buses, coaches, HGVs, water transport as well as trains where the network is not already electrified. Hydrogen's superior weight to energy ratio and the speed and ease that vehicles can be refuelled are considered to be the main reasons for hydrogen's use in heavier vehicles as opposed to an electric only drivetrain. Hydrogen in aircraft fuel was also identified as an option though it was thought that it would be some time before a hydrogen powered aircraft would emerge.

Fleet based vehicles, particularly those operated and contracted by the public sector, were identified as the low regrets option, that would lead the way in hydrogen conversion. Even if hydrogen was not to emerge as a mass option, using hydrogen would still be considered a good way of decarbonising fleet vehicles. Converting a whole fleet creates a level of demand, justifying the investment needed to produce and supply hydrogen at sufficient scale to central refuelling stations. These refuelling stations could potentially be opened to other users, thus serving more than one transport sector. Buses in particular were identified as an ideal end user for hydrogen. Hydrogen buses already operate within Scotland and more are currently on order.



1. 0% (no hydrogen)
2. 10% - 20%
3. 30% - 40%
4. 50% - 60%
5. 70% - 80% (no stakeholder selected)
6. 90% - 100%

Figure 28: Stakeholder responses to 'extent of hydrogen's role for personal transport.

"Hydrogen offers compelling solutions for some forms of transport, for example road freight, hydrogen trains on lines which would be very expensive to electrify, buses, and shipping. An optimal solution for the UK is likely to involve hydrogen for applications such as these and electrification of other transport vectors such as private vehicles"

"Hydrogen use within the transport sector should complement battery electric vehicles rather than competing with them. EVs are particularly useful for urban areas, cars and public transport within cities as well as busy train routes (such as Edinburgh-Glasgow etc). Hydrogen technology could address more challenging areas which are difficult for EVs to enter. This includes shipping, rural train routes, long distance bus routes, heavy-duty transport etc"

Stakeholder questionnaire opinion

ABERDEEN BUSES CASE STUDY

The Hydrogen Bus Project in Aberdeen involves the whole hydrogen system from generation to end use. The project's 10 hydrogen buses are serviced by a refuelling station in Kittybrewster with the capacity to produce 360 kg of hydrogen a day[62]. The refuelling station was also opened to the public in 2018 supplying green hydrogen to private vehicles as well as a fleet of vehicles used by the NHS, a local car club and Aberdeen City Council[63].

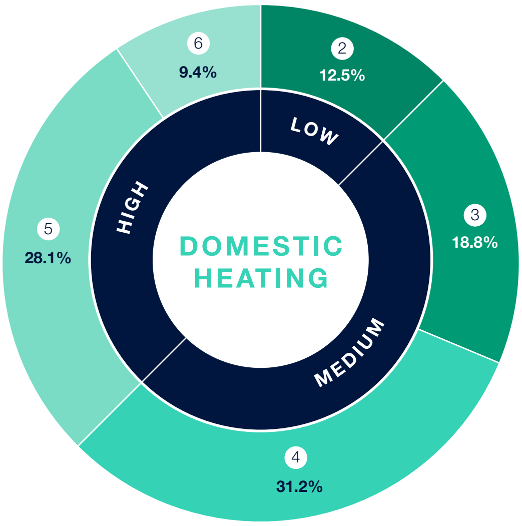
This project was brought up frequently and positively throughout stakeholder engagement, including referring to the project as a strong evidence base for introduction of successful hydrogen refuelling facilities in urban areas. Additionally, stakeholders noted the project had demonstrated a high level of public acceptability for hydrogen within transport.

Whether hydrogen will be used in smaller personal vehicles is more open to question. The majority of stakeholders thought that hydrogen would play no or only a relatively minor role in personal transport. EVs are now established in the personal vehicle market, making it more difficult for hydrogen vehicles to break through. A comprehensive hydrogen refuelling network will be needed to allow for a hydrogen personal vehicles market to grow. Investment in that refuelling network is unlikely unless there is an existing market to serve.

Ultimately the personal vehicle market with its global supply chains, depends on developments at a global level, rather than any decisions that can be made in Scotland, or in the UK. If hydrogen vehicles and the hydrogen refulling infrastructure were to emerge globally, Scotland could be well placed to supply its own, as well as other countries, with the high purity green hydrogen the market would require.

HEATING

Hydrogen could be used to replace natural gas as the main fuel for domestic and commercial space and water heating in Scotland. However, electrification of heating does provide a credible alternative. It was clear that stakeholders believe that decarbonising our domestic heat demand is very challenging. This is reflected in their differing views as to which method would be the most cost effective and practical way of decarbonising heat, with advantages and disadvantages to both[4, 29, 64, 65].



1. 0% (no hydrogen)
2. 10% - 20%
3. 30% - 40%
4. 50% - 60%
5. 70% - 80%
6. 90% - 100%

Figure 29: Stakeholder views on hydrogen usage in domestic heating

Stakeholders are quite split on the role of hydrogen in domestic and commercial space and water heating. Many believe that hydrogen could replace natural gas in the distribution network and be the primary method of decarbonising heating. However, others think that electrification, using air or ground source heat pumps alongside district heating systems in more urban and/or heat dense areas, is a more cost efficient alternative. The potential for hybrid systems, such as heat pumps that include a small hydrogen boiler to raise the temperatures beyond what a heat pump is capable of, was also raised as a potential use for hydrogen[29].

A potential regional approach to using hydrogen for domestic and commercial heating was discussed, in which case some areas would keep a gas network and use hydrogen, whereas others would switch to electrification with heat pumps, and district heating may provide other options. The areas where hydrogen would be used would be where hydrogen can most easily be produced and/or stored or, where there were also large industrial users of hydrogen, so continuing a network would be more viable.

> *"It's entirely feasible that every domestic and commercial boiler can be changed to 100% Hydrogen… When being sold at scale, it is unlikely that a Hydrogen boiler would cost much more than a current natural gas boiler so the cost to the homeowner both in outlay and intrusion and remedial costs to the existing heating system and home is very small if anything more than they experience today with a boiler change. This contrasts significantly with electrification and heat pumps where both the home and the heating system would need significant remedial work"*
>
> Stakeholder questionnaire opinion

Some stakeholders questioned the benefit of feeding green hydrogen in the gas network, where it is likely to pick up impurities, to then be used in combustion boilers. This was highlighted as an ineffective use of what should be considered a ‘higher grade’ product. It was suggested that more value could be gained from using high purity green hydrogen in other applications, such as fuel cells. Blue hydrogen has a lower purity level than green hydrogen, it could potentially be considered lower grade and used in the distribution network for heating.

Blending hydrogen into existing natural gas networks may be considered as part of the gradual step towards the transition to a net-zero economy. Up to 20% by volume, can be blended without changing existing appliances[66]. However, as hydrogen has a lower density 20% hydrogen would only amount to a carbon saving of 7%[67].

> *“Blending hydrogen into the gas networks will give substantial benefits to emissions reductions but heat pumps offer potential electrical solutions also. Blending high-value high purity hydrogen in the gas network seems to miss the point”*
>
> Stakeholder questionnaire opinion

INDUSTRIAL AND POWER GENERATION

Hydrogen is already produced in Scotland for use as a feedstock in chemical production. This hydrogen is currently ‘grey’ and would have to switch to blue or green in the future. The potential role of hydrogen in industry is significant. It is thought that hydrogen could replace natural gas for industrial users connected to the gas network in Scotland. Like with domestic and commercial heating, this could initially be a blend of hydrogen with natural gas, before full conversion to 100% hydrogen.

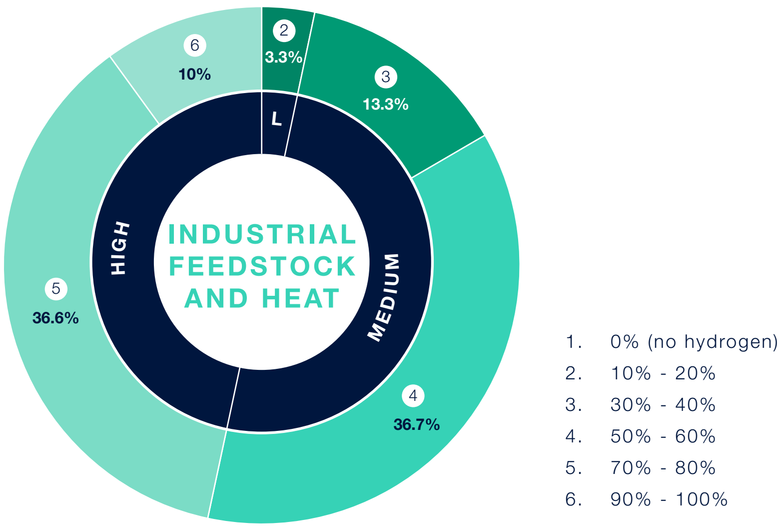


Figure 30: Stakeholder responses to ‘extent of hydrogen’s role within industry (feedstock and heat)’.

Many stakeholders thought that using hydrogen in industry and/or within industrial clusters could act as a demand baseload, enabling hydrogen production at scale which could then enable wider hydrogen usage.

GRANGEMOUTH CASE STUDY

Grangemouth is an industrial cluster and refinery that represents a potential high demand for hydrogen. It currently produces its own 'grey' hydrogen through steam methane reforming and could be encouraged to switch to green or blue hydrogen. Numerous stakeholders highlighted the potential of Grangemouth for a transition into low carbon production of hydrogen.

It was also mentioned that smaller industrial users, outside large industrial clusters, such as food and drink production, could use hydrogen. There may be opportunities for co-location of small scale green hydrogen production particularly in rural or island areas. As an example the whisky and distillery industry was mentioned by some stakeholders as a potential opportunity for decarbonisation with hydrogen. Distillery sites are often remote and not connected to the gas distribution network.

Although there seems to be a good case for using hydrogen in industry to replace natural gas, there are potential alternatives. It was thought that some large industrial users and/or cluster of users could continue to use natural gas with CCUS rather than using hydrogen. Electrification is an option for some industrial processes, such as lower grade heating, but efficiency and technical constraints are a barrier to electrifying higher grade industrial heat applications. Biogas and biomass are also options but could be subject to supply constraints.

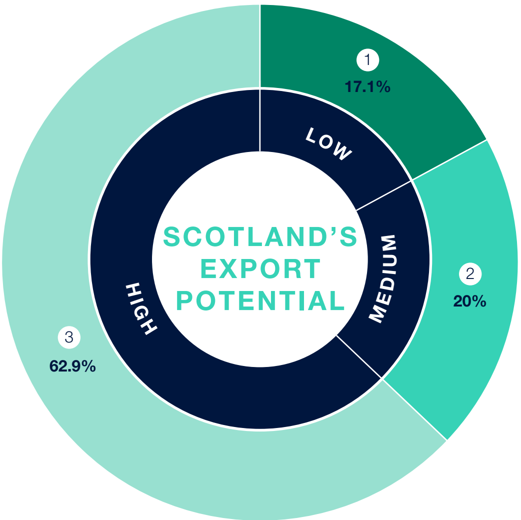
A number of studies and projects have explored the potential for hydrogen in power generation, replacing fossil fuels such as natural gas, in thermal generation[68–70]. However, most stakeholders felt that hydrogen was only likely to play a limited 'peaking' role in power generation in Scotland helping to balance renewable generation.

> *"Large industrial demands for heat in processing could be supplied by hydrogen gas, as these are likely… to have close access to the existing gas network (which by 2045 could be 100% hydrogen based). Distilling tends to be in more rural areas and therefore not likely to be able to access to the gas network, but could use locally generated hydrogen from local renewable energy sources which could create a significant demand/market for community owned energy assets"*
>
> Stakeholder questionnaire opinion

> *"Hydrogen use within industry to deliver high-grade heat is likely to represent a very important role, since power cannot efficiently meet this demand. On the power generation side, hydrogen could replace gas peakers to meet spikes in electricity demand only. Otherwise most electricity consumption will be met from a combination of renewables"*
>
> Stakeholder questionnaire opinion

EXPORT POTENTIAL

The potential for Scotland to become a net exporter of hydrogen, to the rest of the UK and wider Europe, was a common and key topic in stakeholder discussions.



1. Low
2. Medium
3. High

Figure 31: Stakeholder responses to 'potential for Scotland to become a net exporter'.

Many stakeholders felt that Scotland's abundant natural resources, particularly in offshore wind, offered a route to large scale hydrogen production, potentially much more than Scotland could consume domestically. Hydrogen would therefore be a route to 'unlocking' offshore energy, allowing it to be exported to generate revenue for Scotland. It was thought that hydrogen could become a major export product, allowing Scotland to continue its energy tradition and at least partially replace the role that O&G currently plays in the Scottish economy. However, there is an alternative view that export of hydrogen, is less of a priority than decarbonising the domestic economy.

Many stakeholders thought that Scotland could become a major exporter of hydrogen to the European market.

Export further afield was considered less likely given the cost of transportation and alternative international sources.

There are several countries in Europe, Germany for example[17], where hydrogen is expected to play a major role but which do not have the same level of renewable resource as Scotland. However, other countries/regions that could mass produce green hydrogen, are also in proximity to the future major European hydrogen markets. Portugal and North Africa were mentioned as potentially producing green hydrogen from solar at a lower cost than in Scotland. Some stakeholders felt that an export market would take time to develop and that a domestic market in Scotland and in the UK would be the primary market in the short-medium term.

Although Scotland has the potential to produce both blue and green hydrogen, most stakeholders thought it unlikely that Scotland would produce blue hydrogen for export outside of the UK. 'High grade' green hydrogen was seen as a product that other countries would want to import to fully decarbonise their own energy demands. Blue hydrogen can be produced by other countries themselves nearer to the point of use from imported natural gas negating the need to export.

> *"The bulk of the green hydrogen produced will be exported within Europe. There is a possible scenario where Scotland could become the main producer of green hydrogen for the UK domestic market if onshore wind is also used"*
>
> Stakeholder questionnaire opinion

> *"Concerned that the current emphasis on exporting hydrogen at scale from offshore electrolysis or from SMR + CCS will only replicate the situation where the main benefits will go to the energy multinationals and will bypass the Scottish economy"*
>
> Stakeholder questionnaire opinion

5.3 SUMMARY OF CONCLUSIONS

Given the diverse and often competing views including factors described above, it is challenging to accurately predict which applications will transition to hydrogen in the short, medium and long term. From the literature and the stakeholder engagements a picture of overall themes or options are emerging.

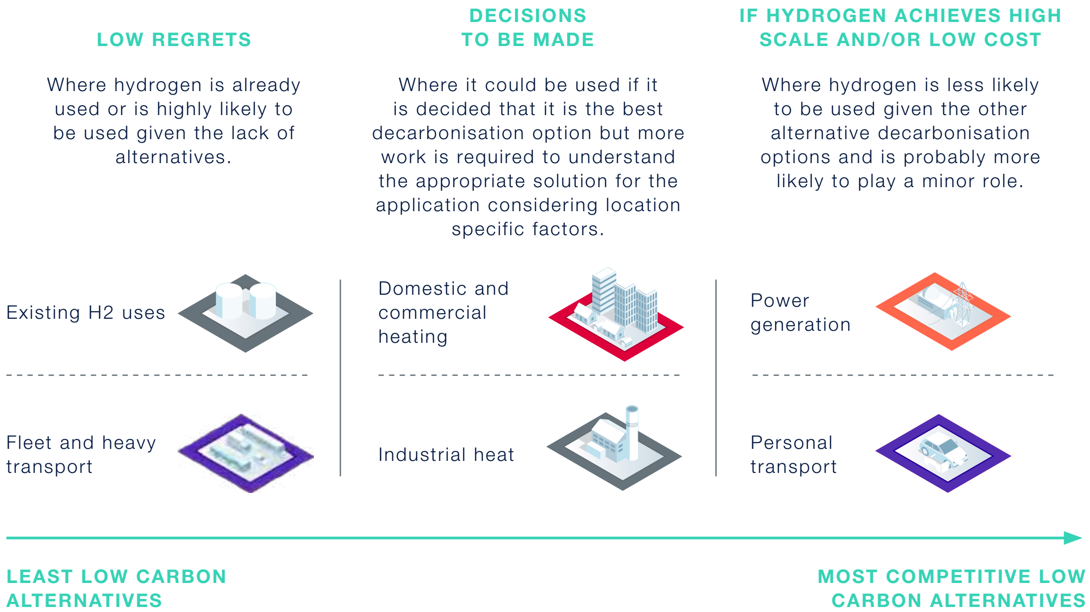


Figure 32: Assessment of relative competitiveness of hydrogen applications

In the stakeholder engagement, a regional split in how hydrogen is used and produced was also discussed. In areas where hydrogen can be more easily produced, it could be used across different sectors giving rise to local hydrogen networks. In other areas hydrogen would be used less, with alternative decarbonisation methods, primarily electrification, used in others.

There are three broad options for the supply of hydrogen:

- Small scale green production using local renewable energy and co-located or very near to demand;
- Large scale green using offshore wind that connects to some form of network; and
- Blue hydrogen, which would be large scale and supply a hydrogen network.

Which production options emerge will depend on the scale and type of demands.

These different options give rise to many ways that hydrogen could develop in Scotland out to 2045. These were used to form potential scenarios, which is discussed in the next section.

6.

SCENARIOS

6 SCENARIOS

6.1 CREATING THE SCENARIOS

Hydrogen is in the early phase of development as a low carbon energy vector and as set out in Section 5 there are various views as to how hydrogen could or should be produced and used. Setting out different scenarios enables an exploration of the range of possible roles that hydrogen could play in a net-zero economy.

The scenarios have been developed to reflect stakeholder views and be distinct and different enough from each other, to test and explore the boundaries of potential future outcomes. They are not intended to be accurate predictions of the future. The actual outcomes are more likely to be somewhere between these scenarios. An initial round of engagement was conducted where a snapshot of potential hydrogen scenarios were identified, more detail in Appendix A3. Following a further round of engagement, these were narrowed down to 3 scenarios.

3 scenarios were consider **Hydrogen Economy**, **Green Export**, and **Focused Hydrogen** It is assumed that the net-zero target is achieved in all scenarios; it is the extent of hydrogen's role that varies in each. Only hydrogen usage is considered in each scenario, it is assumed that other decarbonisation methods, primarily electrification, are also used to a greater or lesser extent in each.

Context	Each scenario envisages a different approach to hydrogen – whether hydrogen is widely used, used more extensively in certain sector or plays only a niche role. The scenarios examine hydrogen usage in Scotland but the UK and international context is also considered.
Demand	Each scenario looks at different ways of using hydrogen in Scotland across 3 main sectors; transport, domestic & commercial heating and, industrial processes & power generation. The scenarios set out whether hydrogen is being used throughout the country, or limited to certain locations and regions. The extent to which Scotland exports hydrogen to the rest of the UK and to Europe is also explored.
Production	Considering the demand, each scenario looks at different methods, scales and locations for hydrogen production. Whether it is large scale blue hydrogen produced around natural gas hubs, large scale green hydrogen production from offshore wind or localised green production from onshore renewables.

Table 04: Scenario variables considered

In each scenario hydrogen makes up different proportions of energy demand in each sector and also has different amounts of hydrogen export. This gives an overall amount of hydrogen in TWh for the three years that have been explored 2025, 2032 and 2045. An assumption has also been made about how hydrogen is produced, with the assumed GW hours of capacity that would be required. Each scenario then has different ways that hydrogen would be transported from sites of production to where it is used, if that is required.

6.2 A HYDROGEN ECONOMY IN 2045

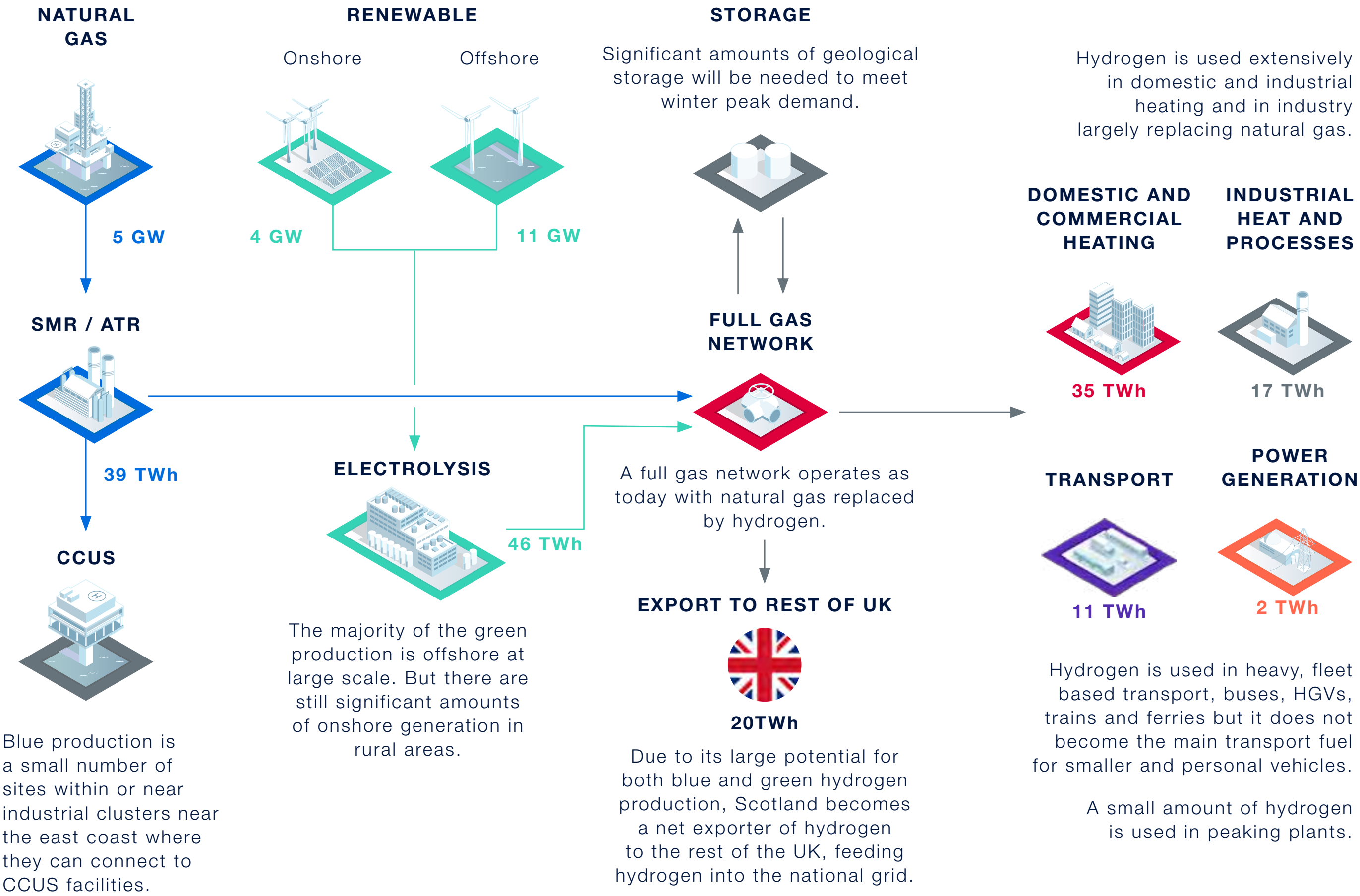


Figure 33: Scenario A) Hydrogen Economy in 2045.

HYDROGEN ECONOMY SYNOPSIS

Hydrogen is seen as one of the main ways that Scotland can reach its net-zero target. It is therefore used extensively throughout the economy.

A cold morning in January 2045…

Graham from Glasgow wakes up on a chilly winter's day at 7am, his house is warm from the hydrogen boiler, this is supplied via a connection to the national grid, which turned on automatically at 6am. After taking a shower with water heated from the same boiler, he catches a hydrogen powered bus to his office work in central Glasgow, the office is heated by a large hydrogen boiler also connected to the national grid.

Sandra in Stornoway also wakes up at 7am, her house and hot water have also been heated by her hydrogen boiler which is supplied by her local gas grid, using hydrogen produced from local renewable sources. She drives her EV to work at the distillery, which uses locally sourced hydrogen for all its energy needs.

KEY CONSIDERATIONS

Conversion of the network

The key driver of this scenario is the conversion of the existing natural gas transmission and distribution network to hydrogen largely decarbonising one of the most challenging sectors - domestic and commercial heating. For this to happen, government and regulatory decisions will need to be taken over the next few years. In the short term it will be critical to focus on building the evidence base on the safety, commercial and consumer acceptability of using hydrogen in the networks and in homes and businesses to support decision making.

Investment requirement

Conversion of large parts of energy infrastructure and building up production capacity will require significant investment. Private investment can be leveraged if a clear revenue stream and business model is in place. Public sector support will likely be required particularly in the early years. This is also will be the case if other decarbonisation methods are used (electrification).

Revenue support requirement in early years of hydrogen usage

In this scenario the bulk of hydrogen is being used in heating and industry where hydrogen is very likely to continue to have a higher unit cost than the current fuel, natural gas in the early years. Over the longer term, carbon taxes could be imposed that will make hydrogen a viable alternative. Before this however, a mechanism that supports the production of and/or use of hydrogen in the network, particularly for heating, will be required. Work is being undertaken by the UK Government on business models for hydrogen production[71].

6.3 GREEN EXPORT BY 2045

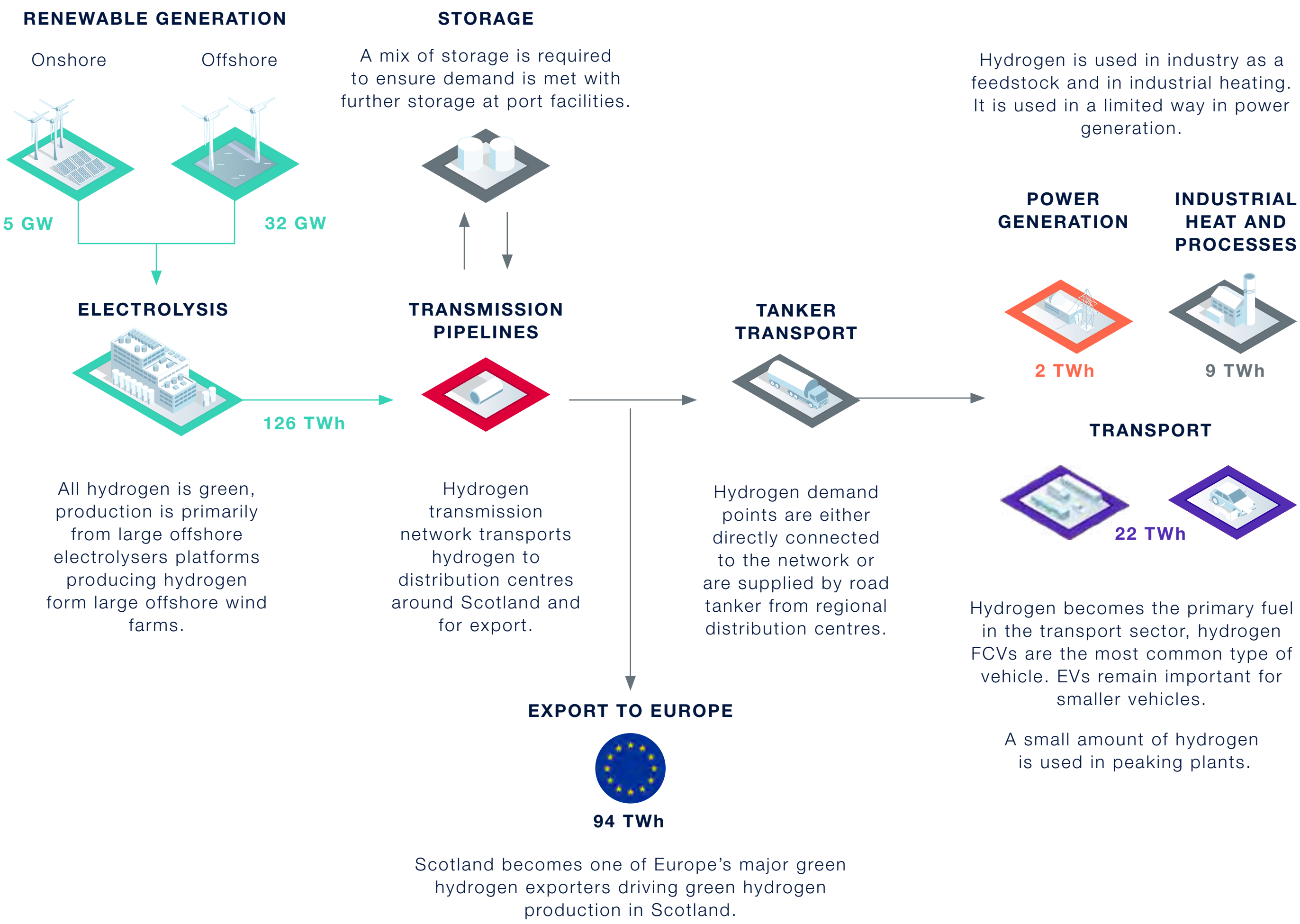


Figure 34: Scenario B) Green Export in 2045.

GREEN EXPORT SYNOPSIS

Hydrogen is produced to harness much of Scotland's renewable energy, becoming a major centre of green hydrogen production in Europe. In Scotland, hydrogen is most used in the transport sector, used across all vehicle types.

A cold morning in January 2045…

Graham from Glasgow wakes up on a chilly winter's morning at 7am, his house has been kept at a constant temperature by an electric air source heat pump, he takes a shower with water heated from a small electric boiler. He catches a hydrogen powered bus to his office work in central Glasgow, the office is connected to a district heating network which has a variety of heat sources.

Sandra in Stornoway also wakes up at 7am, her house and hot water have been heated by a ground source heat pump and an electric boiler. She drives her hydrogen FCV to work, stopping on the way to refuel at the hydrogen refuelling station, which creates its own hydrogen using a local wind farm. She works at the nearby distillery, which uses locally sourced hydrogen for all its energy needs.

KEY CONSIDERATIONS

The feasibility of large scale green production

Producing the quantities of hydrogen required will be a challenge and will require significant amounts of offshore wind deployment and electrolyser capacity. All indications are that this is feasible but will require further research and clear frameworks to make it happen.

Ability of Scottish hydrogen to compete in the export market

Based on current ambitions, it seems likely that that there will be enough demand for imported hydrogen from countries such as Germany. The challenge for Scotland will be if it can supply this hydrogen at a price that can compete with other potential hydrogen sources, such as green hydrogen from solar in North Africa. More work is required to understand what the price of hydrogen from Scottish offshore wind could be and to build links with potential export markets.

An export market is likely to take time to build as initially countries will produce their own hydrogen, therefore a domestic demand will be needed initially to stimulate growth in production.

Hydrogen as the predominate fuel in transport

An ambitious roll-out of hydrogen in transport is anticipated globally, supplying not only fleet and heavy vehicles, but also personal vehicles. Given the global supply chains Scotland, or even the UK, acting alone is unlikely to stimulate this market. This will only emerge if there are significant commitments from governments globally and large scale investment is made by the major global vehicle manufacturers.

It should be noted that a large scale transport market is not a necessity for an export market to emerge. There could still be enough demand for hydrogen in Europe from other sectors e.g. heavier vehicles and for industrial usage.

6.4 FOCUSED HYDROGEN BY 2045

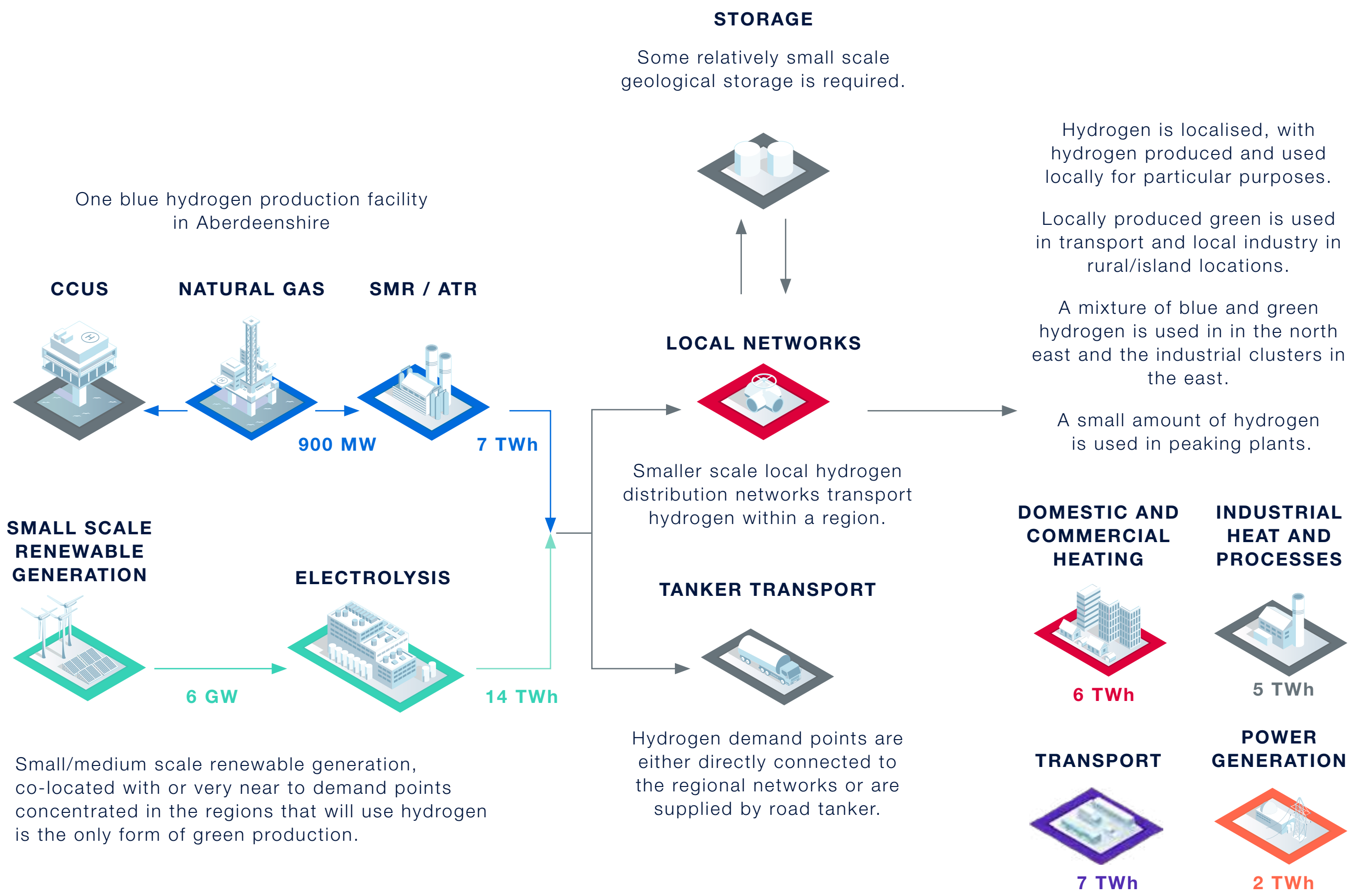


Figure 35: Scenario C) Focused Hydrogen in 2045.

FOCUSED HYDROGEN SYNOPSIS

Hydrogen plays a supportive role in achieving net-zero, being used to decarbonise sectors and areas where it could have the biggest impact. The production and use of hydrogen is regionalised, with hydrogen largely produced and then used locally.

A cold morning in January 2045…

Graham from Glasgow wakes up on a chilly winter's day at 7am his house has been kept at a constant temperature by the electric air source heat pump, he takes a shower with water heated from his electric boiler. He catches an electric bus to his office work in central Glasgow, the office is heated via a connection to a large district heat network.

Sandra in Stornoway also wakes up at 7am, her house and hot water have been heated by her hydrogen boiler, supplied from the local gas grid. She drives her EV to work at the distillery, which uses locally sourced hydrogen for all its energy needs.

KEY CONSIDERATIONS

Small scale

This scenario has hydrogen being produced at small scale, even the blue production facility will be relatively modest. This presents challenges compared to the other scenario due to reduced economies of scale, potentially resulting in higher unit costs than could otherwise have been achieved. However, in the sectors and markets where hydrogen is used it is still the most cost efficient solution compared to other decarbonisation alternatives. This is particularly true in rural or island settings where hydrogen also offers a route to exploit local renewable resources that otherwise could not be fully utilised. Support and co-ordination will be needed.

Hydrogen refuelling for HGVs

Hydrogen is widely used in HGVs, even at higher price points, they are still considered to be much more viable than electric HGVs. This does result in a challenge when it comes to creating refuelling networks for the HGVs, which unlike other HGVs such as buses and local fleet vehicles, will need to be able to travel across the country. Outside of areas where there is a hydrogen grid, HGV refuelling stations would need to be supplied by a combination of co-located hydrogen production and grid electricity to ensure the necessary continuity of hydrogen supply.

6.5 THE DEVELOPMENT OF HYDROGEN IN EACH SCENARIO

Each scenario examines hydrogen's role in the Scottish energy economy by 2045, the year that net-zero needs to be achieved in Scotland. These also explore how hydrogen would develop by 2025 to cover short term developments and then up to 2032 to align with the Scottish Energy Strategy and the Climate Change Plan.

SHORT TERM - 2025

By 2025 hydrogen will only be a limited part of the energy economy in all scenarios, with each scenario showing a different ambition for the amounts of hydrogen that could be used

Hydrogen Economy is the most ambitious at this stage driven by a blue hydrogen facility, Project Acorn[55], coming online and blending hydrogen into the gas network. The other scenarios only pursue green hydrogen for transport and industrial usage. **Focused Hydrogen** has the smallest amount of hydrogen overall, with the focus on using onshore renewables for transport or industrial projects in the north east Aberdeen Hub[72], as well as remote and rural areas.

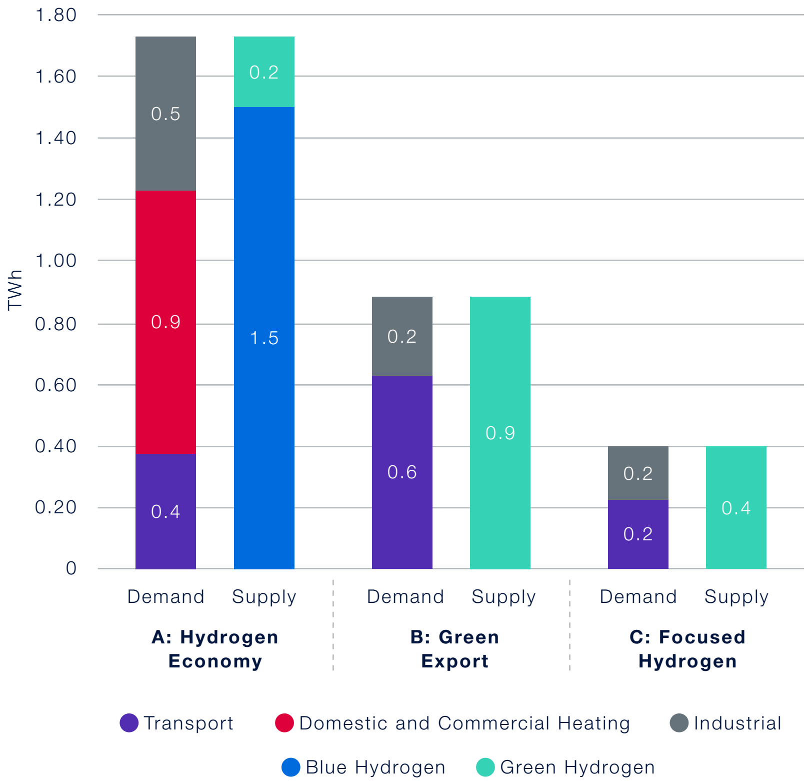


Figure 36: Hydrogen scenarios demand and supply 2025.

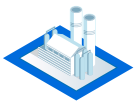
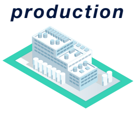
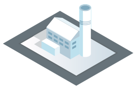
	A. HYDROGEN ECONOMY	B. GREEN EXPORT	C. FOCUSED HYDROGEN
Blue hydrogen production 	Acorn facility in north east provides the majority of production supplying 1.5 TWh of hydrogen from a 200 MW plant.	No blue hydrogen in this scenario.	There is no blue hydrogen at this stage in this scenario as the low level of hydrogen demand does not warrant a blue hydrogen production facility.
Green hydrogen production 	A number of small scale electrolysis production sites spread around the country co-located or very near to demand points totalling around 100 MW, supplying 0.2 TWh of hydrogen. These production sites predominantly use onshore wind including constrained wind.	This is an ambitious scenario with around 400 MW of electrolysers deployed supplying 0.9 TWh of hydrogen in many small/ medium scale onshore production facilities spread throughout the country, co-located or very near to demand points.	Around 150 MW of electrolysers are deployed predominantly supplied with onshore wind co-located or near to demand points. These supply 0.4 TWh of hydrogen and facilities are concentrated in the islands or rural areas. Many will use constrained wind.
Transport demand 	Some limited small scale conversion of public sector fleets to hydrogen, particularly bus fleets, a small number of HGVs and some pilot use in rail and water transport projects. Total transport demand is 0.4 TWh.	A more ambitious programme of hydrogen conversion of public sector fleets and other fleet vehicles, such as local delivery vehicles and HGVs. A small number of public hydrogen refuelling stations serving a very small number of personal hydrogen FCVs at this stage. Total transport demand is 0.6 TWh.	Limited small scale Conversion of public sector fleets, though concentrated in certain areas including the north east as well as island or remote areas. A total of around 0.2 TWh is used in transport.
Domestic & commercial heating demand 	Hydrogen is blended into the gas grid, up to 2% at this stage. This makes up nearly all the demand from the blue hydrogen facility. Some pilot 100% hydrogen projects have been set up serving a very limited number of homes, such as H100 and the local network in Stornoway. Total building demand is 0.9 TWh.	Hydrogen is not used in domestic or commercial heating in this scenario. There is no blending into the gas network.	There is no use of hydrogen in the network yet in this scenario.
Industrial demand 	Gas network connected to industrial customers who use blended hydrogen. Some experimentation with higher hydrogen blends are used in some industrial processes. Total industrial demand is 0.5 TWh.	Hydrogen directly supplies some industrial processes, including users not already connected to the gas grid in more rural areas. All hydrogen production is co-located or very nearby demand so relatively limited. A total of around 0.2 TWh is used in Industry.	Limited usage of hydrogen in industrial processes, using locally produced hydrogen. A total of around 0.2 TWh is used in Industry.

Table 05: Description of each scenario in 2025.

MEDIUM TERM - 2032

The deployment potential in the medium term represents how the sector will evolve over the next twelve years. The larger projects that will be deployed by 2032 will need to start development in the next few years.

By 2032 hydrogen usage has grown in all scenarios, but with different balances of supply and demand. In **Hydrogen Economy** more hydrogen is being used in the gas network and most of this is blue hydrogen. However, more green has now come into production including some large scale production using offshore wind. In **Green Export** there is significant volume of green hydrogen production and the export market is already taking up a significant proportion of demand. In **Focused Hydrogen** there is now a small blue facility which is feeding a network in the north east and there is an expansion in green usage in rural or island locations across all sectors.

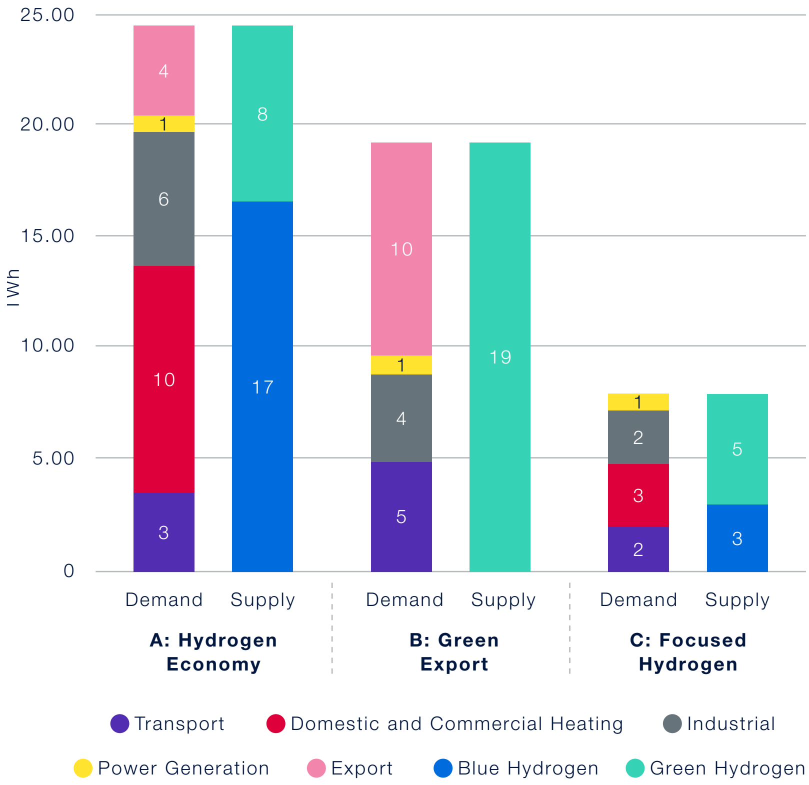


Figure 37: Hydrogen scenarios demand and supply 2032.

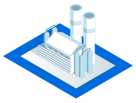
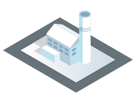
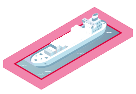
	A. HYDROGEN ECONOMY	B. GREEN EXPORT	C. FOCUSED HYDROGEN
Blue hydrogen production 	The Acorn facility in the north east has expanded and an additional facility producing blue hydrogen is operating around the Grangemouth industrial cluster. Total of 2 GW of capacity supplying 17 TWh of hydrogen.	No blue hydrogen in this scenario.	A small scale blue hydrogen production facility has come online to supply the local network in the north east. Total of 400 MW capacity supplying 3 TWh of hydrogen.
Green hydrogen production 	Expansion in size and number of electrolysers, 2 GW of onshore renewable energy capacity is used to make hydrogen. Large scale production offshore has started to come online reaching around 1 GW of capacity. This hydrogen is connected to the transmission network and/or directly to large demand centres. In total there is around 8 TWh of green hydrogen produced.	Expansion in size and number of electrolysis sites around 4 GW of onshore wind capacity is used to produce hydrogen. Large scale offshore hydrogen production from dedicated wind has started to come online reaching 3 GW of capacity and accounting for around half of all production. Around 19 TWh of green hydrogen is supplied in total.	Expansion in size and scale of onshore renewables, 2 GW of capacity is used to supply around 5 TWh of green hydrogen. There is no large scale offshore in this scenario.
Transport demand 	Further increase in use across fleet transport with more hydrogen buses and other public sector fleet vehicles. Hydrogen also increasingly used in commercial fleets. A total transport demand is around 3 TWh.	Significant increase in hydrogen use in fleet vehicles. Also, significant uptake in personal hydrogen FCVs, driven by ban on petrol and diesel vehicles in 2032. A total transport demand is around 5 TWh.	Increase in fleet vehicle usage in areas where hydrogen is being produced – east coast as well as Island and rural locations. A total transport demand is around 2 TWh.
Domestic & commercial heating demand 	Increase in blending of hydrogen into the gas network, with up to 20%. Some areas of the distribution network have been converted to 100% hydrogen, led by areas close to hydrogen production such as the east coast and independent networks. Domestic and Commercial demand totals around 10 TWh.	Hydrogen is not used in domestic or commercial heating in this scenario. Many buildings are converted to electrification, though the gas network is still running at this stage.	Increase in blending into the distribution network and some limited conversion of the regional network in the north east and the small local 'off grid' networks in island or rural areas. For example, the self-contained gas network in Stornoway. Domestic and Commercial demand totals around 3 TWh.
Industrial demand 	Increased blend of hydrogen in existing industrial gas use, conversion of some industrial processes to 100% hydrogen. Some use de-blend hydrogen from the network and some direct connection of large industrial usage to a hydrogen source. A total of around 6TWh is used in industry and a further 1TWh in power generation.	Some conversion of large scale industrial processes using green hydrogen directly connected to a new hydrogen network. Limited number of small scale industry, in island or rural areas using co-located onshore production. A total of around 4 TWh is used in industry with a further 1 TWh used in power generation.	Increased blend of hydrogen in existing industrial gas use and some limited conversion of small scale industrial processes to hydrogen, particularly in north east and island or rural areas. A total of 2 TWh is used in industry with a further 1 TWh in power generation.
Hydrogen export 	Scotland produces more than it needs and so becomes a net exporter of Hydrogen to the rest of the UK. Around 4 TWh is produced in Scotland and used elsewhere in the UK.	High volumes of hydrogen starting to be exported to the rest of the UK and wider Europe. A total of around 10 TWh of hydrogen is exported outside of Scotland.	No export of hydrogen.

Table 06: Interim medium term development description of scenarios.

NET-ZERO - 2045

By 2045 **Hydrogen Economy** has the largest amount of hydrogen being used in Scotland with 65 TWh. However, it is now **Green Export** which has the largest amount of hydrogen production driven by a large expansion in the use of offshore wind to create green hydrogen in large quantities with transport the biggest user of hydrogen domestically. **Focused hydrogen** has significantly lower usage than the other two, concentrated in a few regions where it is used in a number of applications and in the heaviest, long duty vehicles.

Note that in all scenarios, even **Hydrogen Economy**, a significant amount of energy will be needed from other low carbon sources, principally electricity. The amount of electricity that would be required has not formed part of the analysis.

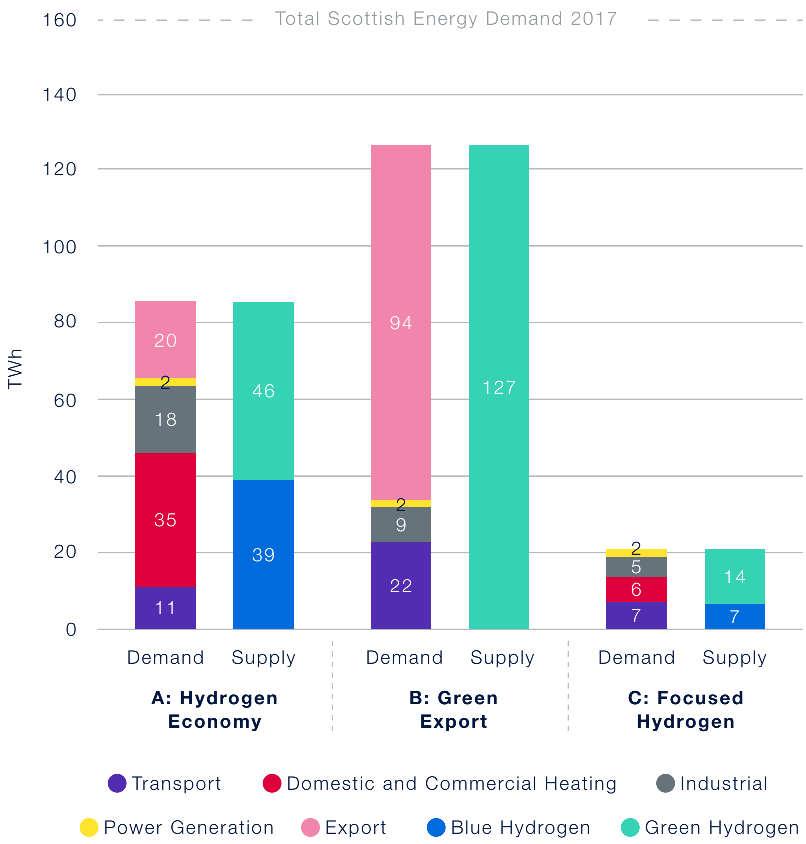


Figure 38: Hydrogen supply and demand 2045.

7.

ECONOMIC ASSESSMENT

7 ECONOMIC ASSESSMENT

7.1 OVERVIEW AND PURPOSE

Realising Scotland's 2045 vision for net-zero will require a transformation of the energy system, providing opportunities for Scottish based companies to generate employment and value for Scotland in the process. The hydrogen sector consists of a complex set of value chains which could either replace existing energy activities or create new avenues for value and job creation. This economic impact assessment (EIA) aims to quantify the socio-economic benefits that could arise from each of the three scenarios explored in the previous section and provide insights into the opportunities they might provide for wealth and job creation.

While the global market for hydrogen technologies remains small, it is growing rapidly and is expected to figure prominently in the future global energy picture. Figure 39 shows the potential areas of value from the hydrogen sector would in Scotland.

Scotland's ability to capture this value will be dependent on whether it already possesses the required skills or whether it can attract and retain these in the future.

Both quantitative outputs and qualitative commentary are provided on the possible economic value created within the sectors that are assumed to convert wholly or partially to the use of hydrogen. These are considered under the three scenarios and in three analysis years - 2025, 2032 and 2045.

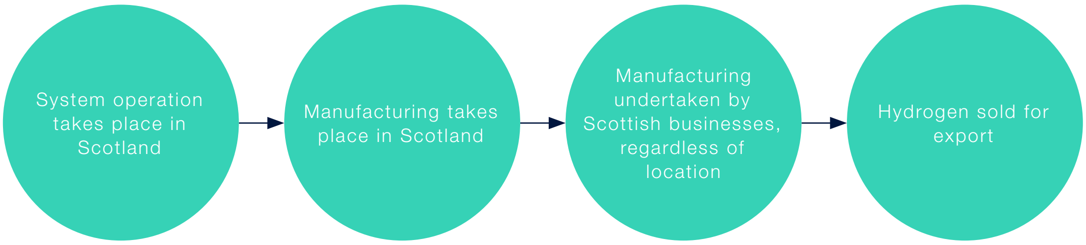


Figure 39: Value creating factors for Scotland

GVA ESTIMATION APPROACH

The approach taken to this EIA consists of two stages: firstly, to estimate the total GVA associated with the hydrogen related activities in each scenario, and secondly to identify how much of that value could be captured in Scotland. The model approach design and key conceptual design aspects are set out in further detail in Appendix A4.2.

The assessment of the value creation potential of activities within the hydrogen sector uses an economic value-added approach. The GVA equates to the sum of compensation of labour, return on capital i.e. annualised CapEx and margin i.e. gross profits. GVA is estimated for each of the hydrogen activities that the scenarios deploy using a bottom-up approach.

For many activities, such as hydrogen vehicles, activity in Scotland will be limited to the sale, installation, operation and maintenance of equipment produced elsewhere, so less detailed cost breakdowns are required in these cases. In these instances, GVA relates to the utilisation of assets and margin of companies operating them as well as the margin for companies installing these assets and the labour they employ.

The analysis is subject to a number of limitations which are highlighted below. More detail can be found in Appendix A4.1.

- The model is neither a full or partial economic equilibrium model;
- The analysis does not represent a full energy system model and only hydrogen related activities are considered; and
- Additionality is only considered from a qualitative perspective since it cannot be quantified without considering the whole system.

7.2 KEY FINDINGS

The EIA estimates the value added that could generate to Scotland under each of the three scenarios. This includes both a quantitative analysis as well as a qualitative assessment. The qualitative assessment includes the capacity of each scenario to deliver regional development, fit with Scottish skills base, extent of use of existing assets and infrastructure, as well as technical and non-technical barriers to the successful delivery of scenarios. In the following sections we provide summary data but a full set of Figure tables is provided in Appendix A4.4.

THE BIG PICTURE

In 2045 the GVA contribution is expected to be highest in **Green Export** in which roughly £26 bn of value is generated. The considerable activity associated with large scale roll-out of green hydrogen production contributes significant added-value and export potential (see Figure 40). **Green Export** also delivers the most employment with more than 300,000 jobs either retained or created (see Figure 41).

By contrast, in **Hydrogen Economy** the more widespread use of hydrogen domestically such as in heat and transport ensures that this scenario also makes a significant contribution in terms of GVA generating £16 bn and 177,000 jobs created. The broader use of hydrogen domestically ensures that value-added and jobs are more evenly distributed across sectors in **Hydrogen Economy** relative to Scenario B.

While **Focused Hydrogen** has lower overall amounts of hydrogen produced and used with hydrogen generating GVA of £5.7 bn and 69,000 jobs, it has the potential to deliver localised value in regions and more even distribution of activities.

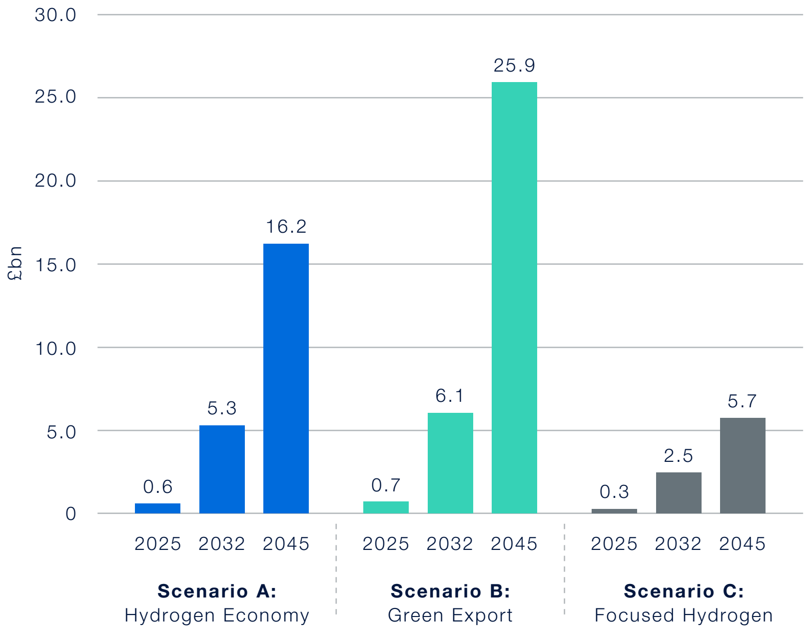


Figure 40: Total Scottish GVA in each scenario (£bn)

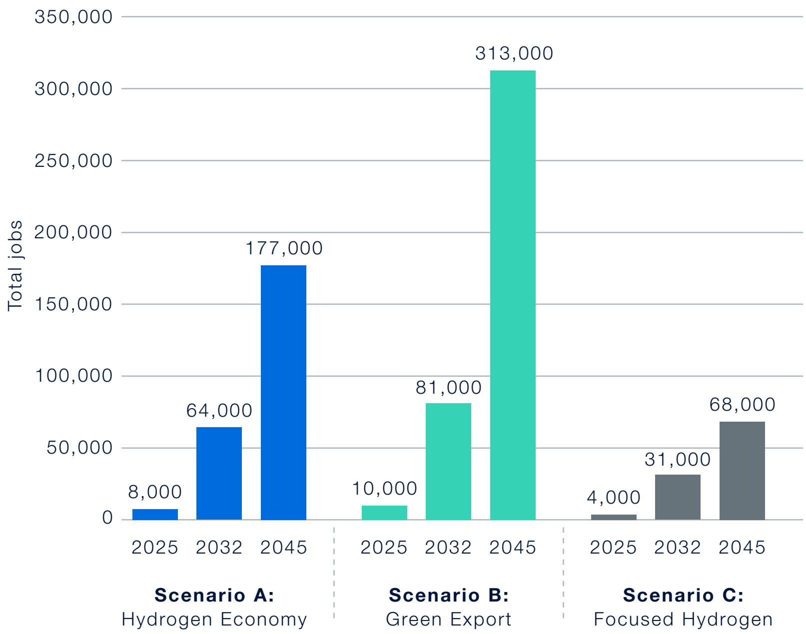


Figure 41: Total number of Scottish jobs in each scenario

Sector contributions to GVA vary according to the features of the scenarios as shown in Figure 42 and Figure 43.

To put these figures into context:

- Total GVA attributable to the O&G sector is estimated at £16 bn[73] while the electricity and gas supply sector represented around £6 bn GVA[74].
- Transport, storage and communication GVA is around £12bn[74].
- The estimated combined employment in the O&G and low carbon energy sectors is nearly 125,000[73].

This is further illustrated in Table 7, which provides a heatmap of the relative contributions to value and jobs by activity in each scenario. Whereas in **Hydrogen Economy** and **Green Export**, the most important contributor of value is hydrogen production, the contributions are more balanced across sectors in **Focused Hydrogen**.

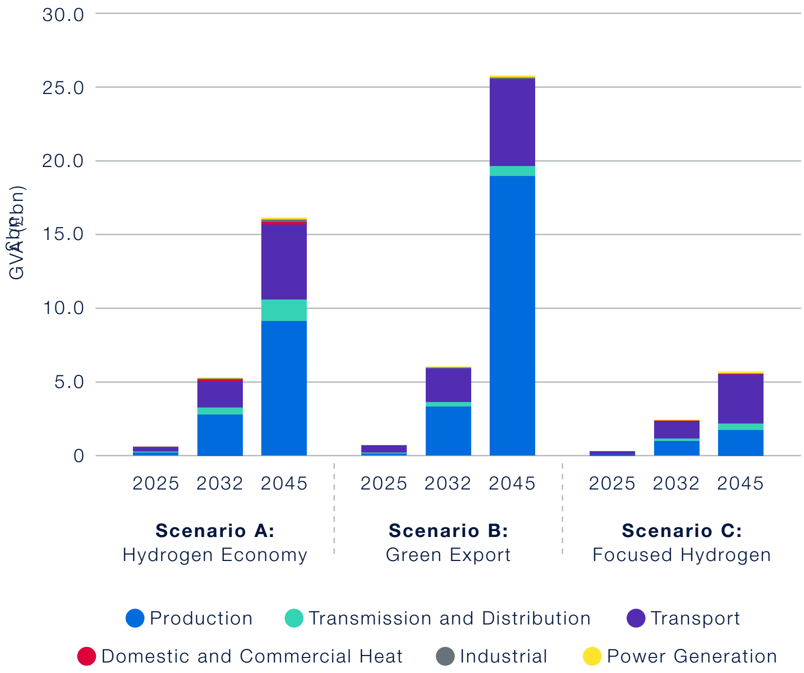


Figure 42: GVA (£bn) by broad economic activity in each scenario

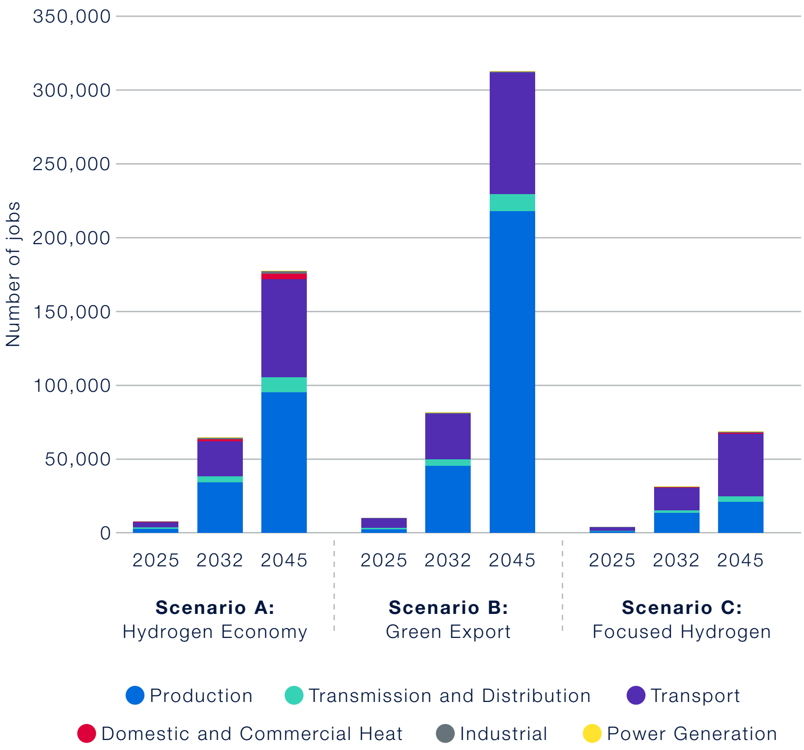


Figure 43: Number of jobs by broad economic activity for each scenario

	SCENARIO A		SCENARIO B		SCENARIO C	
	GVA	JOBS	GVA	JOBS	GVA	JOBS
PRODUCTION						
Onshore Green						
Deployment	0.4%	0.8%	0.2%	0.3%	2.1%	3.9%
Operation	5.1%	5.9%	4.4%	4.6%	22%	22%
Offshore Green						
Deployment	5.2%	11%	10%	19%		
Operation	31%	26%	59%	46%		
Blue						
Deployment	2.6%	5.5%			1.2%	2.2%
Operation	13%	4.6%			6.2%	2.0%
TRANSMISSION AND DISTRIBUTION						
Transmission						
Operation	1.7%	0.3%	0.5%	0.1%	1.5%	0.2%
Distribution						
Operation	6.1%	3.3%	0.0%	0.0%	4.8%	2.3%
HRS						
Deployment	0.6%	1.0%	0.8%	1.2%	1.2%	1.6%
Operation	0.5%	1.1%	1.1%	2.3%	0.8%	1.6%
TRANSPORT						
Buses						
Manufacturing	0.3%	0.3%	0.2%	0.2%	0.4%	0.4%
Transport services	8.3%	11%	5.7%	6.8%	9.3%	11%
HGV						
Transport services	18%	21%	11%	12%	39%	40%
Passenger cars and LGVs						
Retail and maintenance	1.1%	1.9%	3.3%	5.5%	1.5%	2.4%
Trains						
Transport services	2.0%	2.4%	1.3%	1.4%	5.8%	6.3%
Water transport						
Transport services	2.1%	1.4%	1.3%	0.8%	3.1%	1.8%
DOMESTIC AND COMMERCIAL HEAT						
Operation	1.1%	2.2%	0.0%	0.0%	0.6%	1.1%
INDUSTRY AND POWER GENERATION						
Industrial heat and feedstock						
Maintenance	0.9%	0.8%	0.3%	0.2%	0.8%	0.6%

Table 07: Heat map of economic activity in 2045.

High	>5% of scenario total
Mid	2-5% of scenario total
Low	<2% of scenario total

Figure 44 indicates locations around Scotland where value creating activities will likely be undertaken; these vary somewhat according to the scenario being considered. Broadly speaking, specialist manufacturing is likely to be focused in the central belt, the industry sector in Fife and Stirlingshire, and the offshore deployment and support in Aberdeenshire/City of Aberdeen. By contrast, non-specialist manufacturing and transport and heat provision would be relatively more evenly distributed across Scotland.

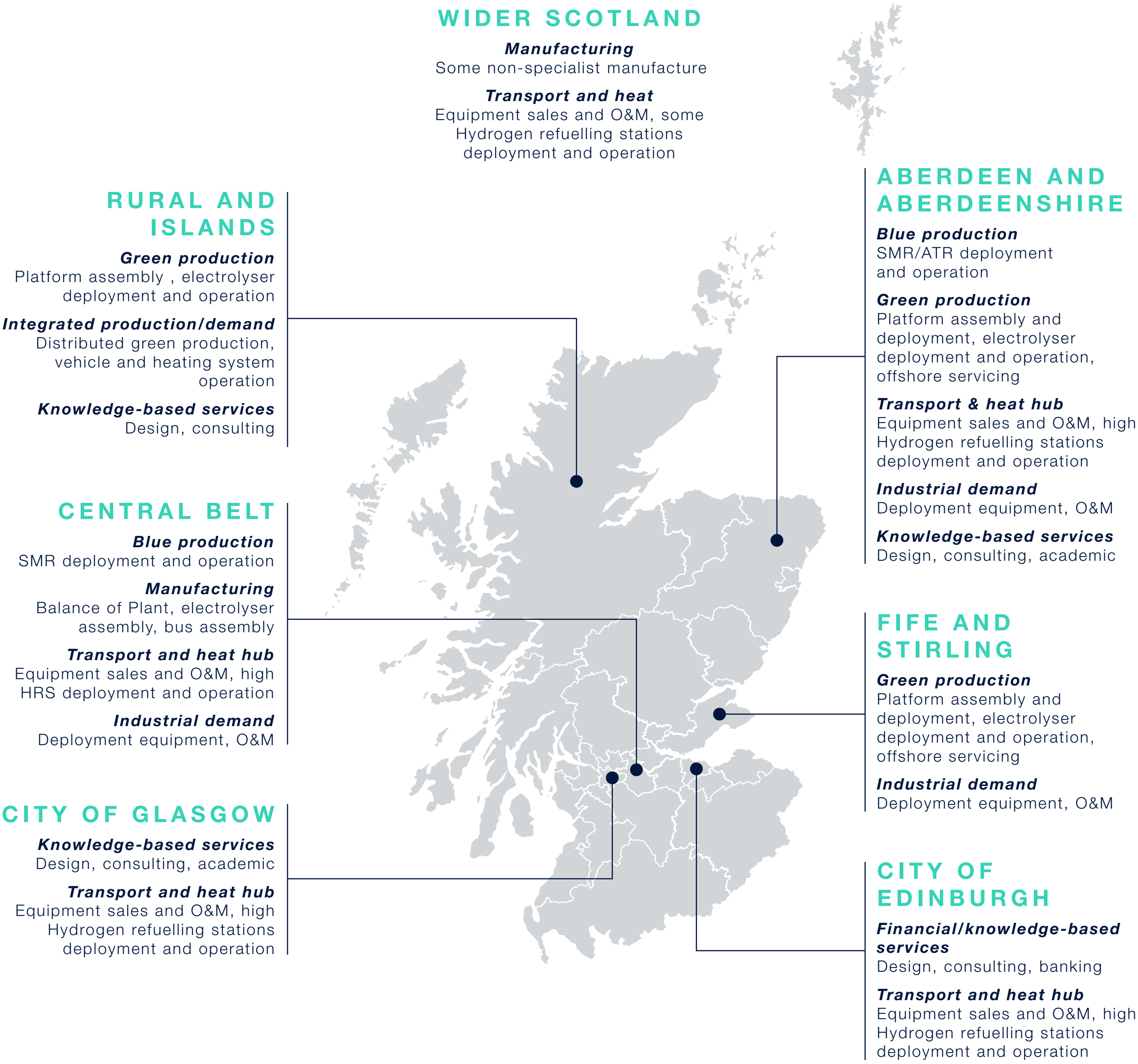


Figure 44: Illustrative location of hydrogen economic activity.

PRODUCTION: THE FUTURE ENGINE OF THE HYDROGEN ECONOMY IN SCOTLAND

Hydrogen production is the biggest absolute contributor of value with the potential to generate nearly £20bn of GVA and employ over 200,000 people in 2045 in **Green Export**. By this date, offshore hydrogen production is by far the biggest contributor of value in both **Hydrogen Economy** and **Green Export**, reflecting the rapid rollout of capacity and the relatively high value added per unit of output.

The total number of jobs created varies from around 20,000 in **Focused Hydrogen** to over 200,000 in **Green Export** in 2045. Jobs are split between construction (28% in **Hydrogen Economy**) and operation (72%) with a tail off in construction jobs expected after 2045 as the build out rate falls. However, in order to meet the necessary build out rates construction is expected to continue right up to 2045, see Figure 45. It is expected that skilled technician and engineer roles to feature highly, reflecting the complex nature of the activities.

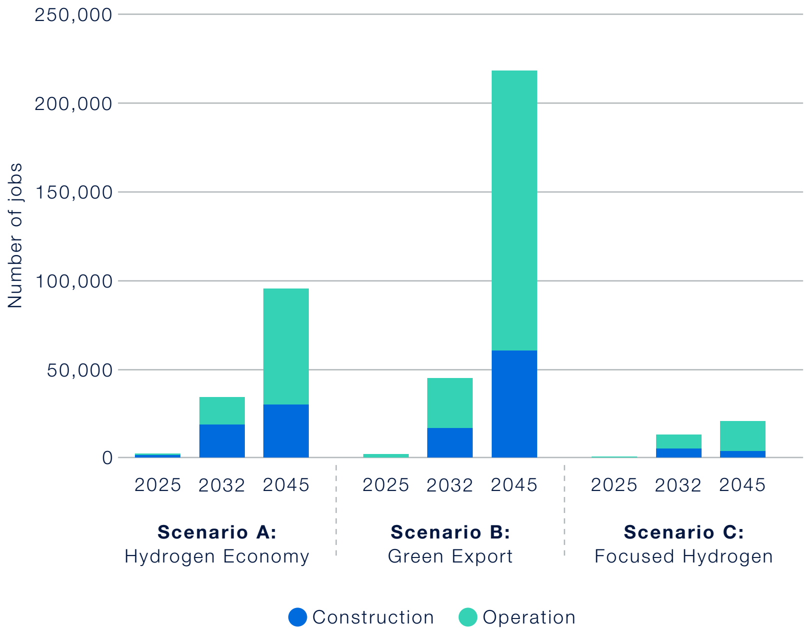


Figure 45: Number of jobs in hydrogen production by ONS category

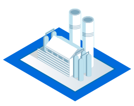
SUB-SECTOR	SOURCE OF VALUE	ADDITIONALITY	SKILLS & LOCATION
Onshore green production  ***Jobs in 2045*** A: 9.600 B: 1,000* C: 4000 * Note that this figure is low owing to slow down in onshore construction rates by 2045.	***Manufacturing*** Some manufacture of installation materials. Possible electrolyser system integration in ***Hydrogen Economy*** and ***Green Export***. ***Deployment*** Electrolyser & onshore wind turbine installation. ***Maintenance*** Electrolyser and wind farm maintenance. ***Hydrogen production*** Generation and sale of green hydrogen.	Majority of these activities are new* especially in the case of green hydrogen for export. * Note that this may in part replace O&G activities that currently meet the equivalent energy demand.	Significant skills in deployment of bulk onshore wind power. Manufacturing mostly in the central belt. Operation and maintenance could be quite distributed.
Offshore green production  ***Jobs in 2045*** A: 65,700 B: 202,900	***Manufacturing*** Some manufacture of installation materials. Possible electrolyser system integration. ***Deployment*** Electrolyser and offshore wind turbine installation. ***Maintenance*** Electrolyser and wind farm maintenance. ***Hydrogen production*** Generation and sale of green hydrogen including export.	Majority of these activities are new although note that this may in part replace O&G activities that currently meet the equivalent energy demand.	Significant skills in deployment of offshore renewables. Construction, deployment and servicing centred around existing shipyards and offshore O&G locations, e.g. Aberdeen. Manufacturing mostly in the Central Belt which may also be the logical location for potential electrolysis integration plant. Additional port activity associated with services and potentially export of hydrogen.
Blue production  ***Jobs in 2045*** A: 18,000 C: 3,000	***Manufacturing*** Some manufacture of installation materials. ***Deployment*** Installation of SMR/ ATR plant plus CCUS facilities. ***Maintenance*** SMR/ATR plant maintenance. ***Hydrogen production*** Generation and sale of blue hydrogen.	Majority of these activities are completely new although note that this may in part replace O&G activities that currently meet the equivalent energy demand.	Coincides with existing O&G and petrochemical, e.g. Grangemouth and St Fergus. Offshore servicing capability also relevant for CCUS in depleted oil & gas reservoirs.

Table 08: Production activities.

Scotland has a natural advantage in green hydrogen production but there are gaps in the supply chain.

The green hydrogen supply chain includes both small scale and large scale production requirements and similar supply chain structures apply to both onshore and offshore scenarios. The supply chain elements required to manufacture green hydrogen using electrolysis, including renewable electricity supply, is relatively well supported in Scotland. Scotland has good system integration skills and considerable offshore expertise from the O&G sector which could be leveraged for the green hydrogen supply chains. It has a range of fabricators and non-specialist component manufacturers that could effectively compete for non-hydrogen specific supply chain elements. It also possesses a wide range of engineering design and academic research capabilities that could be brought to bear.

By contrast, Scotland has limited expertise in the manufacture of key system elements including electrolysers and wind turbines. These would be high value added activities as would be the specialist extended supply chains that go with them. Scotland could benefit from attracting an existing or new electrolyser producer to locate an assembly plant in the region and this would not only generate direct jobs and value but may also lead to the establishment of a local supply chain to service that plant. The value of electrolyser assembly has been estimated in **Green Export** to reach £1.5 bn in 2045, creating over 3,500 jobs. However, the value attributable to the wider supply chain could increase this further if manufacturing component elements, could also be established locally.

Scotland has a natural advantage in green hydrogen production given the huge potential offshore and onshore resource and for this reason, attracting local electrolyser or wind turbine assembly plant to Scotland is a credible goal.

However, supply chain competition will be fierce and electrolyser firms may seek to centralise activities in order to benefit from scale economies. In order to fully capitalise on the opportunity from green hydrogen production consideration should be given to how best to nurture these core activities. This may require supportive policies and will be subject to the establishment of an adequate supply chain, whether locally or extended.

The sheer scale of investment required to realise the green production potential in **Hydrogen Economy** and **Green Export** presents challenges in terms of mobilising capital and resources and the effort required should not be underestimated. Access to capital could present a major hurdle to the achievement of these scenarios.

Key skills and supply chain present in Scotland

While Scotland has a limited indigenous manufacturing supply chain for provision of key plant like wind turbines, it has some key existing and transferrable skills from its renewable and energy sectors including:

- A strong existing renewables sector with many onshore and offshore wind developers with locations and active projects within Scotland. The supply chain capabilities are centered around development, construction including civil and electrical contractors, and operations.
- As electrolysis projects have developed in Scotland organisations are building up capabilities to support the development of these projects. EMEC first procured a hydrogen electrolyser in 2015 and have since gone on to expand their portfolio of hydrogen projects.
- A number of Small to Medium Enterprises (SMEs) in Scotland specialise in areas of the electrolyser supply chain. Examples include: Pure Energy Centre, an electrolyser integrator or assembler located in Shetland and; Logan Energy a system integrator and operator based in Edinburgh.
- Scotland's O&G sector has transferrable skills in the supply and service of process engineering kit.

Scotland may be able to leverage its flagship CCUS project to develop know how in blue hydrogen

Many of the supply chain elements required for the production of blue hydrogen from methane via steam methane reforming (SMR) or auto thermal reforming (ATR) exist already in Scotland's O&G industry. The same is also largely true for CCUS. SMR/ ATR plants are typically bespoke and built at the installation site, with many of the components, e.g. pressure vessels, pipework and supporting steelwork, being relatively standard items which could be manufactured in Scotland.

There is limited potential for the development of core intellectual property (IP) around SMR/ATR and CCUS although the integration of these two elements for blue hydrogen production may offer opportunities. These are high value added activities but at present much of this IP is being captured outside Scotland by the large industrial companies and engineering, procurement and construction vendors. As with green hydrogen production, the natural advantage offered by Scotland in terms of access to natural gas supply and carbon storage potential opens the door to local firms being able to capture more of the value chain. The extent to which Scotland is able to generate IP in this area will also determine the extent to which this sector could offer export potential in the same way that Scotland exports O&G expertise recognising that there are strong incumbent players.

Further value-added opportunities may exist in liquid fuels production

The analysis assumes that hydrogen is used and exported in gaseous or liquid form but in practice hydrogen may be transported and ultimately used as ammonia, methanol or any number of synthetic hydrocarbons from methane to jet fuel. If these fuels and energy carriers become established, then they are generally most economically co-produced in the same location as hydrogen. Scotland may therefore be in a position to add further value to the hydrogen being produced by synthesising these fuels and chemicals. The skills assessment points to the presence of relevant skills in Scotland which could be exploited to realise this additional economic opportunity.

Key skills and supply chain present in Scotland

The skills associated with blue hydrogen production commonalities with both the construction and operation of thermal and gas processing plants, and to offshore exploration and production (E&P) activity. Scotland does not have indigenous suppliers of the main plant and equipment, and a significant proportion of the O&G supply offshore vessels are international. However, the significant indigenous supply chain could support in a range of areas, including:

- A number of services companies and contractors supporting E&P have the skills to design construct and operate the pipelines, platforms and wells associated with CCUS infrastructure.
- The skill set from Scotland's onshore O&G processing terminals such as INEOS at Grangemouth and the various facilities at St Fergus, alongside historical expertise in thermal plant operation from utilities such as SSE, and the civil and process contractors that support them will translate into onshore hydrogen production
- Several O&G operators including SGN and National Grid are participating in both the Acorn Hydrogen and Acorn CCUS projects being developed by Pale Blue Dot Energy at St Fergus.

TRANSMISSION AND DISTRIBUTION: BUILDING ON SOLID FOUNDATIONS

In **Hydrogen Economy** where the existing network is maintained, the GVA contribution from the transmission and distribution sector is modest at roughly £1.5 bn in 2045, while sector jobs could be significant reaching nearly 10,000. As discussed in Table 9, these jobs will be largely retentive of existing economic activity in the transmission and distribution of natural gas and will be relatively distributed across the country.

SUB-SECTOR	SOURCE OF VALUE	ADDITIONALITY	SKILLS & LOCATION
Transmission  ***Jobs in 2045*** A: 400 B: 200 C: 100	***Maintenance*** Maintaining the transmission network. ***Hydrogen transmission*** Transport and sale of hydrogen to the distribution grid and large end-users.	Hydrogen would result in the continued operation of the existing gas network which would lead to job and value retention which otherwise would be lost as the grid is decommissioned.	The network is widely distributed but most of the O&M economic activity will be centred on existing facilities, e.g. SGN head office in Edinburgh. Emerging skills in storage.
Distribution  ***Jobs in 2045*** A: 5,900 C: 1,600	***Maintenance*** Maintaining the full distribution network in ***Hydrogen Economy*** and reduced network in ***Focused Hydrogen***. ***Hydrogen distribution*** Delivery and sale of hydrogen to end-users.	O&M of the existing network would lead to job and value retention.	While the network is widely distributed most of the O&M economic activity will be centred around existing facilities, e.g. SGN head office in Edinburgh. Emerging skills in storage.
Hydrogen refuelling  ***Jobs in 2045*** A: 3,700 B: 11,000 C: 2,200	***Deployment*** Installation of hydrogen refuelling stations. ***Maintenance*** Maintaining hydrogen refuelling stations. ***Forecourt services*** Sale of hydrogen to hydrogen refuelling stations customers.	Installation could be considered additional while hydrogen refuelling stations operation is likely to be replacement or retentive.	Fairly distributed activity reflecting the location of stations; more concentrated in centres of population and highly regionalised in ***Focused Hydrogen***.

Table 09: Transmission and distribution activities.

Scotland has a good range of skills in transmission and distribution

Scotland possesses a good range of skills in the field of pressurised gas transmission and distribution and this is supplemented with capabilities in petrochemicals and O&G. The use of hydrogen in the gas network will be explored in the H100 project, a world first for the supply of 100% hydrogen to a cluster of homes in the Fife region, and this might allow the development of specific IP. Scotland has developed emerging skills in hydrogen storage which will be required to act as a buffer to account for short and long term variations in production and end use and could take the form of both pressure or cryogenic vessels and geological stores such as porous rock or salt caverns.

Much of the value associated with the use of hydrogen as an alternative to natural gas in the gas network could be captured by Scottish firms. An opportunity to capture additional value and jobs in the deployment of new transmission or distribution grid infrastructure also exists, particularly in **Green Export**. However, since the geographic detail needed to evaluate this is beyond the scope of the current study, this has not been included.

Scotland has limited skills in hydrogen refuelling stations technology development

Scotland has some existing capabilities in the operation of hydrogen refuelling sites, such as the ones in Aberdeen to service the bus fleet. However, to date the sites have been built and maintained by non-Scottish entities. Much of the value associated with the deployment and operation of hydrogen refuelling infrastructure could be captured in Scotland although this may not be very high value added if the core IP is owned outside Scotland. Efforts to localise the design and manufacture of elements of the hydrogen refuelling stations could be initiated in order to maximise the benefits captured in Scotland, although core IP is likely to remain with the industrial gases companies, e.g. Air Products, BOC Linde.

Key skills and supply chain present in Scotland

Scotland has an indigenous supply chain that supports the import, export, distribution and storage of natural gas. That supply chain is likely to decline in a strong electrification scenario, but will be transferrable to hydrogen depending on the scenario:

- SGN, the Scottish Gas Distribution Network Operator (GDNO), are developing a world leading demonstration project intending to build a 100% hydrogen network in Scotland.
- Scotland's chemical industry, largely centered around Grangemouth and Mossmoran, could provide the skills and infrastructure required to convert and transport hydrogen derivatives including ammonia, organic hydrogen carriers or metal hydrides.
- The ports and harbors of Scotland support a diverse set of offshore industries including the import/export of natural gas. Specialised facilities exist in the Port of Grangemouth and Peterhead.

TRANSPORTATION: POTENTIAL OPPORTUNITY IN BUSES AND BESPOKE HEAVY DUTY VEHICLES

Hydrogen transport services make a significant contribution to value added in all scenarios, with transport GVA in **Green Export** reaching nearly £6 bn in 2045. HGVs and buses generate most value added, primarily from their operation, although much of this is substitutive and not additional, see Figure 46.

Job numbers are also significant with employment of around 80,000 in **Green Export** in 2045. Employment spans manufacturing and retail but most of the job creation/retention is expected in vehicle operation and maintenance (see Figure 47). These activities are generally not additive but are well distributed across Scotland as discussed in more detail in Table 10.

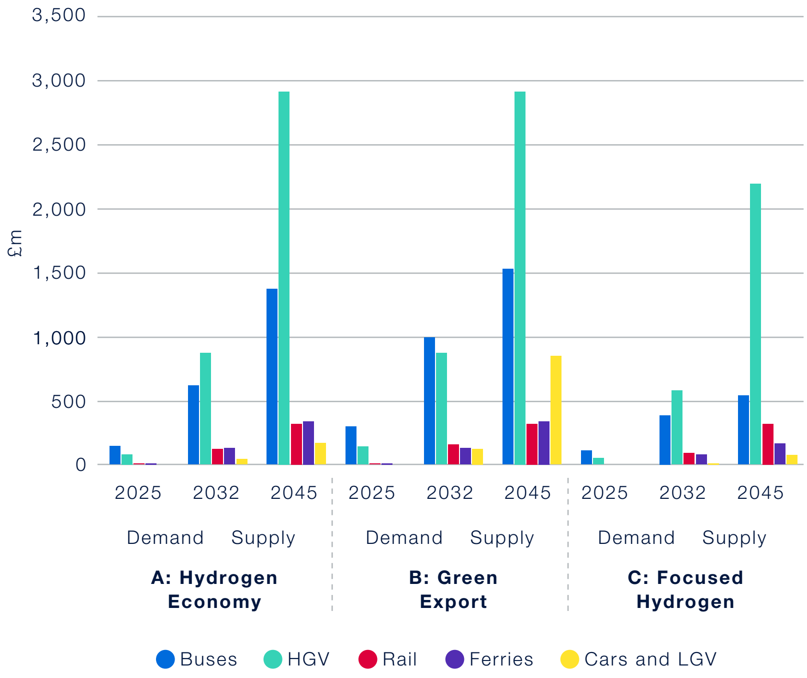


Figure 46: GVA (£m) by transport sector

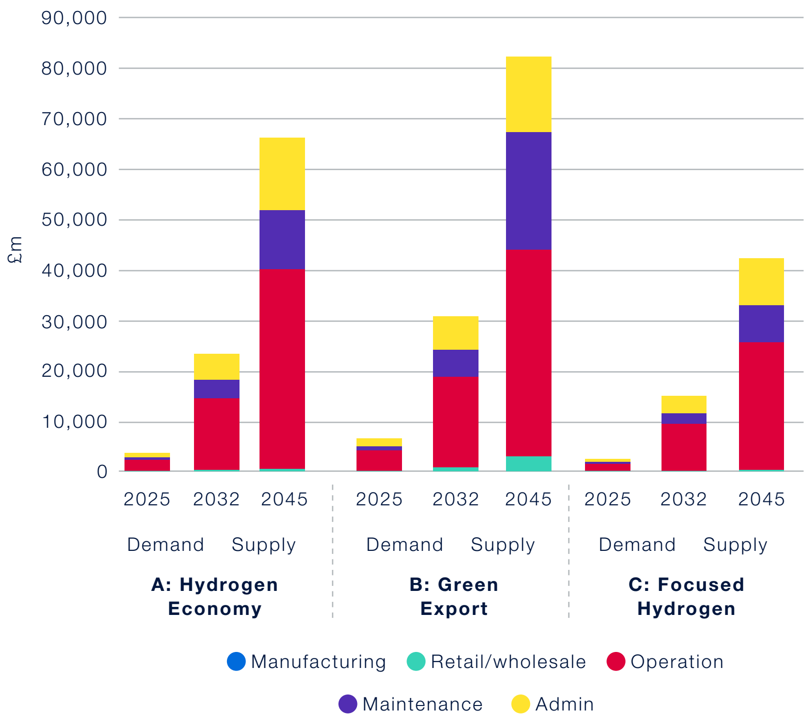


Figure 47: Number of jobs by ONS category

SUB-SECTOR	SOURCE OF VALUE	ADDITIONALITY	SKILLS & LOCATION
Buses ***Jobs in 2045*** A: 19,600 B: 21,900 C: 7,700	***Manufacturing*** Bus assembly and system integration. ***Maintenance*** Maintaining the bus fleet. ***Transport services*** Provision of services though operation of the bus fleet.	Generally not additive since hydrogen buses replace existing vehicles and services. Manufacturing, for example at Alexander Dennis Limited (ADL), could be additional.	O&M widely distributed with all towns/cities operating bus fleets. Manufacturing is assumed concentrated in Falkirk where ADL has its manufacturing facility.
HGV ***Jobs in 2045*** A: 36,500 B: 36,500 C: 27,400	***Maintenance*** Maintaining the HGV fleet. ***Transport services*** Provision of services through the operation of the HGV fleet.	Generally not additive since hydrogen trucks replace existing vehicles and services.	Jobs and value added are expected to be centred around existing depots and refuelling locations, e.g. Clydeports.
Passenger cars and LGVs ***Jobs in 2045*** A: 3,400 B: 17,000 C: 1,600	***Retail*** Sale of passenger cars and LGVs. ***Maintenance*** Maintaining passenger cars and LGVs.	Generally not additive since hydrogen passenger cars and LGVs replace existing vehicles and services.	Dealership and maintenance activities are widely distributed.
Trains ***Jobs in 2045*** A: 4,300 B: 4,300 C: 4,300	***Maintenance*** Maintaining hydrogen trains. ***Transport services*** Provision of services through operation of hydrogen trains.	Generally not additive since hydrogen trains replace existing vehicles and services.	Jobs and value added are expected to be centred around existing depots and refuelling locations.
Water transport ***Jobs in 2045*** A: 2,400 B: 2,400 C: 1,200	***Maintenance*** Maintaining hydrogen vessels. ***Transport services*** Provision of transport services through operation of hydrogen vessels.	Generally not additive since hydrogen vessels replace existing vessels and services.	Operation of ferries is concentrated on the west coast, and Western and Northern Isles.

Table 10: Transport activities.

Bus manufacture could represent a significant opportunity for Scotland

Vehicle manufacturing and assembly are considered relatively high value added activities and are often associated with deep supply chains. Scotland has existing capabilities in bus and ferry manufacture and a limited supply chain surrounds these activities in Scotland. It is thought that an opportunity may exist to extend this capability into hydrogen/fuel cell alternatives although there is limited track record to date. The analysis only considers the manufacture of buses at the existing ADL plant in Falkirk for domestic deployment whereas scope exists to expand this activity if export opportunities present themselves, whether to the rest of the UK or overseas.

While the local market in Scotland is probably not large enough to make it attractive enough for a vehicle original equipment manufacturer (OEM) to locate a fuel cell car assembly plant it may be worth considering whether to support an opportunity in more specialised vehicles. If an extended hydrogen vehicle supply chain emerges around ADL this may support such an initiative, with potentially common supply chain elements. It should be emphasised that an established local extended component supply chain is lacking today.

Scotland has existing capabilities in the operation and maintenance of all vehicle/vessel types and it is anticipated that these could be redeployed to hydrogen/fuel cell alternatives. Indeed some of this expertise already exists based on the participation of Aberdeen in fuel cell bus trials.

Emerging opportunity in hydrogen marine

The analysis only considers the value of operating hydrogen domestic ferries and other water transport however there are potentially some opportunities in the wider fleet, e.g. offshore service vessels. The Scottish marine sector have been involved in designing a prototype hydrogen vessel as part of the HySeasIII project[21] which could evolve into a value generating activity. Recent evidence of Scottish shipbuilding being able to compete in international markets is limited and recent troubles with the ferry programme give cause for concern. However, the emergence of a hydrogen ferry manufacturer may present an interesting opportunity for Scotland and further investigation of this would be warranted.

Key skills and supply chain present in Scotland

While Scotland generally has a limited supply chain in the design and construction of vehicles and vessels, it has made some early movements into hydrogen transportation including:

- Scotland has led the development of hydrogen fuel cell projects with the Aberdeen Hydrogen Bus project operating 10 hydrogen powered buses. Through this project Aberdeen City Council have become involved in the pan-European JIVE Scottish bus manufacturer ADL has also become involved in JIVE and subsequently launched their first hydrogen powered double decker bus in 2019.
- In marine transportation, the Scottish Marine sector are involved in developing one of the world's first hydrogen ferries in collaboration with St Andrew's University and Orkney Island Council as part of the HySeas III project.
- Brodie Engineering, a train refurbishment firm in Kilmarnock, has been contracted to convert a ScotRail train to hydrogen power using technology developed by St Andrew's University and London based Arcola. The converted train will be tested in Scotland and is part of Transport Scotland's work exploring alternatives to diesel fuel.

HEAT, INDUSTRY AND POWER: AN IMPORTANT DRIVER OF DEMAND

Value added from the domestic and commercial hydrogen heat sector is expected to be modest at £177 m in 2045, although the number of people employed in the sector may be quite sizable reaching nearly 4,000 jobs in 2045 (Figure 48). This apparent discrepancy reflects the fact that these jobs come from maintaining a very large number of domestic boilers. No boiler manufacturing activities are expected. However, the heat and industry sectors could be an important driver of demand and underpin the roll-out of production capacity. The contribution from industry and power generation is also modest, reaching a maximum of £263 m in 2045 in **Hydrogen Economy**. Similarly, job creation is modest reflecting the economies of scale realisable at large facilities with around 1500 jobs created.

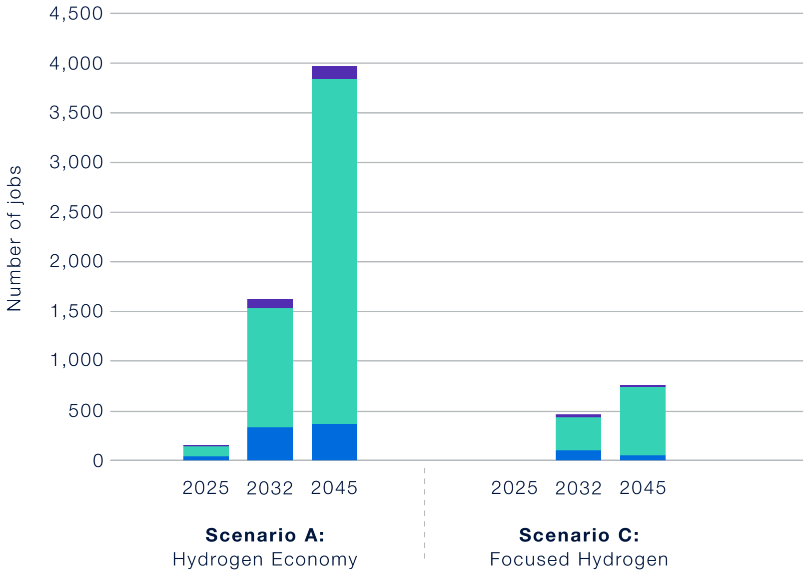


Figure 48: Number of jobs in provision of domestic and commercial heat by ONS category

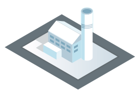
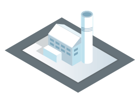
SUB-SECTOR	SOURCE OF VALUE	ADDITIONALITY	SKILLS & LOCATION
Domestic and commercial heat  ***Jobs in 2045*** A: 4,000 C: 800	Installation and especially maintenance of boilers. Note no hydrogen is used in this sector in ***Green Export***.	O&M of equipment is not additional but would lead to job and value retention. New equipment installation may be additional if installation is quicker than usual replacement cycle.	In ***Hydrogen Economy***, highly distributed activity but concentrated in areas where the penetration of gas grid most extensive. Concentrated deployment in ***Focused Hydrogen***.
Industrial heat  ***Jobs in 2045*** A: 1,500 B: 800 C: 400	***Maintenance*** Maintaining industrial boilers.	The replacement of equipment may provide some additional value but activity is largely replacement / retention.	GVA and jobs likely to be centred around existing industrial sites on the east coast, e.g. Grangemouth.
Power generation  ***Jobs in 2045*** A: 100 B: 100 C: 100	Operation of hydrogen-fuelled generating plant - relatively sizable in ***Focused Hydrogen***, given low overall usage, but limited in ***Hydrogen Economy*** and ***Green Export***. May be some value added from the refitting of plants but this has not formed part of the analysis.	Likely to be replacement / retention as hydrogen replaces natural gas.	Locations around existing gas- or diesel-generating plants, e.g. on the islands and some onshore locations such as Peterhead.

Table 11: Domestic, commercial and industrial heating activities.

Opportunity in fuel cells for power and heat

Scotland has an opportunity to build on existing skills in higher value added activities such as the design and production of stationary fuel cell for power and heat applications and leverage it into the heat sector. Outside systems integrators such as Logan Energy, Scotland's capabilities are currently limited and consideration should be given as to whether support mechanisms for technology developers could be used to further this sector. However, it should be emphasised that well established and well capitalised players in this domain may limit the potential for Scottish players to emerge. Scotland does possess extensive skills in heat and power generation system installation, operation and maintenance which could likely be repurposed to hydrogen based systems, retaining value and jobs in Scotland.

Key skills and supply chain present in Scotland

There is a relatively limited indigenous supply chain of OEMs supplying key equipment for heating applications. However, the existing gas supply chain has transferrable skills and some highlights in terms of Scottish experience include:

- Doosan Babcock, an international engineering company with an office in Renfrew installed the UK's largest hydrogen fuel cell system at the Aberdeen Exhibition and Conference Centre (AECC) which provides heat and power for the venue.
- SGNs H100 project will lead to the development of local supply chains for the installation and maintenance of domestic hydrogen equipment.
- Enocell, based in Lanarkshire, specialise in fuel cells that are designed to provide power generation in rural communities that have limited access to grid power. The company was founded in 2011 as a spin out from the University of Aberdeen.
- There are a number of SMEs in Scotland that can provide subcomponents for fuel cell manufactures, for example Ceimig, based in Dundee, specialise in precious metals and manufacture fuel cell catalysts.
- Logan Energy has capabilities in stationary fuel cell integration and deployment with installations around the UK including the Palestra building in London. They also carried out the integration work on the Levenmouth Community Energy.

8.

KEY MESSAGES AND NEXT STEPS

8 KEY MESSAGES AND NEXT STEPS

It is clear that hydrogen will play a role in decarbonising Scotland's energy system and economy by 2045, though the extent of that role is uncertain. Targeted investment in hydrogen can help Scotland to realise a secure, flexible, cost effective and low carbon energy system while achieving green economic recovery from the Covid-19 downturn and a Just Transition from an O&G dominated economy.

8.1 KEY MESSAGES

The stakeholder engagement and the analysis conducted for this assessment identifies key themes that need to be considered if Scotland is to maximise economic benefit and overcome the challenges of decarbonisation.

Scotland could grow a strong hydrogen economy supporting jobs and GVA growth

Value can be captured through investing in innovative technology and commitment to infrastructure.

Green hydrogen production from offshore wind can be a catalyst to generate nearly £20 bn of GVA and employ over 200,000 people in 2045. The natural advantage that Scotland has in renewable energy supply, combined with the considerable offshore expertise from O&G, can be leveraged to position Scotland as a key exporter of high purity, green hydrogen.

Blue hydrogen production can be used to develop expertise and services in the sector that could be exported worldwide, in a similar way to the capabilities in the O&G sector that are exported currently.

However, gaps remain in the supply chain for both green and blue production that will need to be filled in order to ensure that Scotland gets the most out of a transition to hydrogen.

Co-ordination of efforts across industry and government

Better co-ordination will enable an efficient transition and ensure economic opportunities are maximised.

There is already significant momentum from both industry and government in hydrogen demonstration and development, supported by a complex network of research and innovation programmes and funding sources. The regulatory framework is complex, risking possible gaps and overlaps in terms of roles and responsibilities.

Co-ordination of these programmes across the hydrogen supply chain will ensure efficient delivery and value for money. A number of stakeholders raised the possibility of:

- A dedicated co-ordination/regulatory body for hydrogen, similar to the role of the OGA;
- A body co-ordinating research and innovation, similar to the role of the Catapults or OGTC; and
- Creation of a public-private sector leadership steering group to ensure that industry and government work closely in developing and delivering the strategy.

Clear strategy with proposed ambitions

There is significant focus globally on the opportunities that can be realised from developing an indigenous hydrogen economy, that aligns with the needs of a global market.

Germany, the Netherlands, Australia, South Korea and Japan are among nations who have published national strategies with clear direction of travel and ambitious targets that align with their specific strengths. These strategies encompass aspects including decarbonisation of the energy system, industrial strategy and effective use of natural resources.

Stakeholders were clear in their desire for Scotland to develop a clear central strategy, setting out its proposed ambition for hydrogen, aligned with its strengths. Such a strategy will give industry a clear signal of ambition and allow industry and investors to respond with confidence.

Going beyond the pilot project stage and into commercial scale projects

To date, most hydrogen projects in Scotland and the UK have been wholly or significantly paid for by the taxpayer, through public funding, or bill payer through Ofgem innovation funding. This will need to continue in the short term in order to ensure that the evidence base for a hydrogen transition is solid. However, for many stakeholders the next important step is to move beyond the small pilot stage and into large scale commercial projects.

To achieve this, viable business models that allow for and stimulate private sector investment need to be imagined. The UK Government is exploring the creation of business models that would support hydrogen production and is considering related policy mechanisms[71]. Expediting the implementation of an enduring fiscal regime will be critical to creating the pipeline of post demonstration projects.

Maintaining flexibility

Hydrogen is still in the early stages of commercialisation as an energy vector and could develop in several different ways.

This assessment concluded that there are demand applications that are low regrets, e.g. heavy duty transport, and should be moved to widespread deployment in the short term. For others, such as domestic and commercial heating, more development and demonstration are required to create an evidence base which will inform the optimal solutions.

Ruling out options now would be premature, in the context of seeking net-zero 2045 solutions. At this stage all options, including blue and green hydrogen, or use of hydrogen in the gas heating network should be kept open.

Hydrogen needs to be seen within a whole energy system context

Hydrogen will complement increasing electrification, by improving system flexibility and resilience. Some of its benefits will only be understood when looking at the wider system context.

Understanding where hydrogen is the optimal decarbonisation solution needs to take into consideration the geographical/ regional specific requirements, and how that complements the wider system functionality.

There is little consensus in studies undertaken to consider the macro-economic benefits of electrification and hydrogen pathways, due mainly to residual uncertainties about costs, captured benefits and technology pathways. Support should be given to all viable options, but as the evidence base builds, decisions should be taken on preferred solutions in the context of the wider system.

Speed of deployment

If Scotland wants to capture more of the economic value from hydrogen activities it needs to act quickly and decisively.

For example, Scotland could become a centre for skills and services in green hydrogen production with global potential. Moving determinedly to deploy significant production capacity would require the creation of supply chains close to deployment. This has the potential to attract manufacturing activity to Scotland for electrolysis systems or key demand applications like buses.

However, if Scotland is slow to deploy, then there is a risk that supply chains will be developed elsewhere, reducing the opportunity in Scotland.

8.2 CONSIDERATIONS FOR NEXT STEPS

The study and engagement identified a number of specific areas for further focus that could underpin growth in the hydrogen energy vector.

REPORT FINDING	ADDITIONAL INSIGHT / KNOWLEDGE REQUIRED
Green hydrogen is likely to feature in some capacity in Scotland's energy economy and its role will likely grow in the long term.	• Stakeholders agreed that green hydrogen is the ultimate goal and that Scotland should move decisively to crystallise that opportunity. • Scotland should set an ambitious 2032 target and ensure there is a fiscal regime to support delivery against the target as has been done by the EU and other countries such as Germany. Clear future targets for green hydrogen production will give producers and investors a clear framework to work within. • Action should be taken to cement economic value in Scotland e.g. system integration or manufacturing.
Scotland could become a large scale producer of green hydrogen for export, most likely to Europe.	• The cost competitiveness of green hydrogen from Scotland needs to be explored and understood particularly in relation to other potential sources of green hydrogen production including solar power in the southern Europe and North Africa. • The practicalities of mass export of large amounts of hydrogen need to be investigated, i.e. whether hydrogen is transported by ship (as liquid hydrogen, ammonia or via liquid organic hydrogen carrier) or via gas pipeline. • The needs and requirements of potential export markets, such as Germany, need to be understood with some degree of co-operation between import and export markets.
Hydrogen is an opportunity for rural areas and islands to harness their renewable energy sources.	• Rural areas and islands need support to unlock their renewable potential by understanding what the best options for hydrogen use locally are considering distribution of supply, demand and export. • There is a need to evaluate how hydrogen costs compare to the current energy costs in order to understand where it can be deployed.

Table 12: Further focus areas.

REPORT FINDING	ADDITIONAL INSIGHT / KNOWLEDGE REQUIRED
Blue hydrogen could be an important part of Scotland's future in the short to medium term.	• Commitment should be made to build out of a blue hydrogen project (such as Acorn), which can provide a low cost supply at volume in the short term. • Evaluation should be undertaken of the scale up of production of blue hydrogen in conjunction with wider CCUS initiatives. • Consideration should be given on how this would help to match supply with demand and potentially allow the gas network to be leveraged.
There are low regret options for building hydrogen demand in the short to medium term, especially fleet vehicles. This can be led by buses but also includes HGVs, non-electrified rail and water transport.	• Support mechanisms for vehicle operators, bus companies, local councils etc should be explored. • Further transport routes that could benefit from hydrogen could be identified and existing routes should be expanded. • Points of demand need to be matched with sufficient, secure supply of high purity hydrogen. • Continue to build upon existing transport initiatives such as the: - Automotive Industry Advisory Group - H2 Accelerator in St Andrew's - Michelin Scotland Innovation Parc
Hydrogen is a good option for industrial applications.	• Need to understand more about Scotland's specific industrial demands e.g. process heat or feedstock. The demands of a few users will have a large proportional impact. • There is an opportunity to potentially accelerate deployment of hydrogen for specific demand sectors such as food and drink production.
There are decisions to be made as to whether hydrogen should be used in the gas distribution network. Hydrogen is a potential option but there are other options, electrification, district heating and CCUS (for industry).	• It is likely that all heat decarbonisation solutions (hydrogen, electrification, CCUS and district heating) will be required to decarbonise the range of heat applications. Research needs to continue to determine the best decarbonisation solutions for each application (domestic, commercial and industrial heat) considering safety, techno-economic viability and consumer acceptance. • This should include at scale demonstration of hydrogen for heating in domestic, commercial and industrial applications.
Hydrogen production, either blue or green, could bring significant economic value and jobs to Scotland particularly if more of the supply chain could be captured within Scotland.	• Development of supportive policies and assistance to establish an adequate supply chain, whether locally or extended will unlock value. • Undertaking detailed analysis and mapping of the hydrogen production supply chain, examining Scotland's strengths and gaps could help to identify areas where Scotland could look to build capabilities in order to capture GVA and jobs. • Targeted innovation funding can allow for energy skills transition.
There is a complex regulatory, framework, and a lack of clarity of roles in some areas.	• There is a need to work with key UK and Scottish regulators to ensure that the regulatory position for hydrogen is clearer. • Funding mechanisms need to be developed to support the policy objectives. • Coordination is required to ensure value-for-money from innovation project funding.

Table 12: Further focus areas (continued).

9.

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