ARUP

DECEMBER 2020

# SCOTTISH HYDROGEN ASSESSMENT

## *Supporting Appendices*

Scottish Government
Riaghaltas na h-Alba
gov.scot

Scottish Enterprise

HIE

# APPENDIX CONTENTS

ARUP

SCOTTISH HYDROGEN
ASSESSMENT PROJECT

# APPENDIX 1

## *Scottish Hydrogen Economy*

Scottish Government
Riaghaltas na h-Alba
gov.scot

Scottish Enterprise

HIE

## A1.1 DESCRIPTION OF SCOTTISH HYDROGEN PROJECTS

| NO. | PROJECT NAME | PROJECT DESCRIPTION |
|---|---|---|
| **01** | Project Acorn[1] | Project Acorn comprises of two elements: a hydrogen production plant and a CCUS storage facility, which is expected to be the first in the UK. The production plant will be a 200 MW low carbon hydrogen plant using Johnson Matthey technology, which will blend hydrogen into the National Transmission System at St Fergus. Blending into the gas network will start at 2% and increasing to 100% conversation of the local network (Aberdeen and Moray), ultimately decarbonising the gas at St Fergus Gas Terminal and providing hydrogen for power generation. The CCUS transport and storage facility will make use of three redundant pipelines (Miller Gas Pipeline, Goldeneye Pipeline and Atlantic Pipeline) and will deliver a CCUS project, to sequestrate carbon dioxide from multiple sources, expected to be St Fergus Gas Terminal, Peterhead Power Station and Grangemouth Industrial Cluster (via the NTS pipeline). The project is currently at pre-front end engineering design (FEED) stage and has recently received government funding of £2.7 m via the UK Government's Hydrogen Supply Programme to support its progression as well as additional support from the Scottish Government's Energy Transition Fund. |
| **02** | Hydrogen Offshore Production Project[2] | The Hydrogen Offshore Project (HOP) is exploring how existing North Sea O&G infrastructure in the Orkney islands could be used to deploy a low carbon hydrogen demonstration project using the Flotta Oil Terminal. So far, the project has considered how a variety of hydrogen production technologies could be suitable in an offshore setting that would sit at the heart of an Orkney Hydrogen Hub, specifically Steam Methane Reforming (with CCUS), Gas-to-Graphene, PEM Electrolyser and Alkaline Electrolyser. The project is currently investigating viable technology solutions and business cases whilst also developing a test site.<br><br>For the feasibility study, the project received £500k in funding the first round from the UK Government's Hydrogen Supply Programme but was unsuccessful in the second round and is now investigating alternative funding routes to support testing. |
| **03** | Surf 'n' Turf[3] | The Surf 'n' Turf project has delivered a 500 kW green hydrogen production facility in the Isle of Eday. The hydrogen is produced using tidal power from turbines at EMECs test and demonstration site and the Eday Renewable Energy community's 900kW wind generation. The hydrogen is stored and transported to a fuel cell in Kirkwall for local ferries. During development, the project received £1.46 m for construction funding from Scottish Government's Local Energy Challenge Fund. |
| **04** | Dolphyn ERM[4] | Project Dolphyn is exploring the possibility of using Deepwater Offshore assets to generate Local Production of Hydrogen. The project will use 4 GW floating offshore wind technology to generate green hydrogen for 1.5 m homes. Initially, the asset will be a demonstrator with a capacity of 2 MW and expanding to 10 MW as the next phase. An initial feasibility study has been undertaken and the project is now undertaking detailed design and securing consents for a financial investment decision in 2021. ERM received approximately £430k of funding for the project from the UK Government via the Hydrogen Supply Competition. |
| **05** | Grangemouth[57] | The Caledonia Clean Energy Project5 investigated the possibility of producing hydrogen as part of the larger CCUS activities on the Grangemouth site. The project looked at using the existing Feeder 10 pipeline to transport captured carbon away from Grangemouth and towards St Fergus. The produced hydrogen would be used to meet industrial demands onsite as well as potential transport demands in the local area. |
| **06** | Chapelcross | The Chapelcross nuclear power station ceased energy generation in 2004 and the site is in the process of being decommissioned. Current about 60 ha of the 200 ha site is available for development with significantly more becoming available over the next decade, with the final clearing process scheduled for between 2090 and 2095. The Chapelcross Transformation Programme is currently investigating a number of options for development at the large site, including the potential for a hydrogen production site. |
| **07** | Green Hydrogen for Scotland | A partnership between Scottish Power Renewables, BOC and ITM Power to provide a green hydrogen production and refueling facility located on the outskirts of the city. This will be powered using both solar and wind to power a 10MW electrolyser. This project is aiming to deliver green hydrogen into the commercial market by 2022. |
| **08** | H100[6] | The H100 project aims to build a 100% hydrogen network to supply 300 homes with green hydrogen, a world first. The project is currently investigating the commercial and technical feasibility, front-end engineering designs, and exploring two possible locations for the network: Levenmouth in Fife and Machrihanish in Argyll. Alongside this, SGN are developing safety and evidence case for a hydrogen network, considering operational procedures, hydrogen logistics, metering and appliance validation, odorant and gas detection and commercial arrangements. SGN have received funding from Ofgem's network innovation allowance (NIA) scheme as well as recent funding from the Scottish Government. |

**Table 1:** Description of the Scottish hydrogen projects

| NO. | PROJECT NAME | PROJECT DESCRIPTION |
|---|---|---|
| 09 | LTS Futures – Grangemouth to Granton[7] | This SGN lead project investigated the technical and regulatory issues with using existing pipelines to transport hydrogen through the local transmission system (LTS). This study found that 91% of SGN's local transmission network would likely be capable of moving hydrogen. |
| 10 | Aberdeen Vision | SGN, alongside partners National Grid, Pale Blue Dot, ERM and DNV-GL, are aiming to inject 2% hydrogen into the gas network in order to determine whether this is commercially viable. The project would use blue hydrogen produced at St Fergus Gas Terminal and involved injection into the distribution network throughout Aberdeen and Aberdeenshire. The project is also investigating a 100% hydrogen pipeline direct to Aberdeen that would allow a blend of up to 20% hydrogen into Aberdeen's gas network. |
| 11 | Hydrogen Bus Project[8,9] | The Scottish Government has provided funding of £6.5 m over the past few years to support the introduction of Hydrogen Buses in the City of Aberdeen. The current fleet of 10 hydrogen buses have collectively covered 1 over million miles. Fifteen new buses are procured and arriving this year (2020) and a further 10 buses are being considered as part of the Scottish Government's £62m Energy Transition Fund launched in June 2020.<br><br>The hydrogen bus fleet has been running since 2015. Hydrogen is produced from a 1 MW electrolyser and fuel a fleet of ten buses, operated by First and Stagecoach. Other infrastructure developed by the project includes a refuelling station (which currently services 65 vehicles) and a hydrogen safe maintenance facility. The scope of the project was expanded to include 15 double decker buses due to be operational in 2020. To support this demonstration project, £19 m of funding was received to support the deployment from Europe, UK Government, Scottish Government, Innovate UK, SSE, SGN, Scottish Enterprise, First, Stagecoach and Aberdeen City Council (bringing together High VLo City and HyTransit projects). |
| 12 | HySeas I-III[10] | The HySeas project is a research project that has been delivered across three phases with the ambition to deployment hydrogen vessels around the Islands of Orkney.<br><br>The first phase (HySeas I) investigated the theory of deployment hydrogen vessels and was followed by a technical and commercial study in HySeas II. The final phases of the programme aim to construct and test a vessel hybrid fuel cell power system at full scale, specifically trying to demonstrate the integration of fuel cells with a hybrid electric drive system. On successful completion of phase 3, Transport Scotland will fund the construction of a roll-on roll off hydrogen/ electric drive train passenger ferry with the integrated full cell and drive system technology. |
| 13 | HySpirits[11] | The HySpirits project is exploring how hydrogen could be used instead of liquid petroleum gas at a craft gin distillery in Orkney, reducing its environmental impact of carbon emissions. The project has received just under £150k from BEIS to undertake a feasibility study for the site and to develop the hydrogen system design and specification. If successful, it will be the first-ever hydrogen gin distillery. |
| 14 | HyTrEc[12] | The Hydrogen Transport Economy for the North Sea Region (HyTrEc) aims to promote and advance the use of hydrogen as an alternative energy vector across all onshore and offshore transport modes in the North Sea Region; specifically, the project will:<br>• Establish a North Sea Hydrogen Transport Stakeholder Group to develop strategies and initiatives for hydrogen usage.<br>• Undertake a transnational pilot study looking at the accessibility and connectivity of existing hydrogen corridors and hydrogen supply chain infrastructure development.<br>• Pilot hydrogen technologies.<br>• Develop a North Sea Region education forum. |
| 15 | HyDIME[13] | HyDIME is a 12-month project to design and integrate a hydrogen /diesel dual fuel conversion 50kW auxiliary power system on a commercial ferry operating between Kirkwall and Shapinsay; the project is:<br><br>Securing the required marine licenses and regulatory approvals for the use of hydrogen in a marine environment.<br><br>Demonstrating and testing of the system in sea trials.<br><br>Delivery of the scale up plan will integrate with the Surf 'n' Turf project; the project has received over £400k from InnovateUK. |
| 16 | SWIFTH2[14] | The Scottish Western Isles Ferry Transport using Hydrogen (SWIFTH2) project is exploring the usage of green hydrogen through electrolysis to power two ferry routes. Following production using wind generation, the hydrogen would be stored and then used as marine fuel for the local ferries. Scope of the project so far has been a high-level feasibility study considering suitable ferry routes and location for the onshore wind farm. The feasibility study has been supported by funding from the Scottish Government's Low Carbon Infrastructure Transition Programme (LCITP). |

**Table 1:** Description of the Scottish hydrogen projects (continued)

| NO. | PROJECT NAME | PROJECT DESCRIPTION |
|---|---|---|
| 17 | HyFlyer[15] | The HyFlyer project aims to demonstrate the viability of a hydrogen fuel cell powertrain technology for aviation and ultimately undertake a test flight of 250-300 nautical miles from Orkney and Cranfield. Hydrogen will be created from renewable energy sources and the project will develop the fuel cell technology through a phased approach from battery power to hydrogen power for integration into a six-seater aircraft for testing. Outputs from the project will be used by ZeroAvia to support their ambition to be operating the technology commercially from 2022. The project has received £2.7 m in funding from the UK government supported by BEIS, Aerospace Technology Institute (ATI) and Innovate UK. |
| 18 | Stornoway hydrogen refueller | The project introduced demonstrator hydrogen infrastructure in the Outer Hebrides; providing hydrogen from biogas, derived from local waste, to local refuelling stations to vehicles and fleet owners, including the Royal Mail. More recently the Outer Hebrides Local Energy Hub project has recommissioned the refueling station and created a link to a local fish farm. The fish farm is able to use the oxygen from the electrolysis process and is considered an exemplar circular economy project. |
| 19 | Hydrogen refueling station[16] | Logan Energy have recently funded and installed a public 350 bar hydrogen refuelling station at their Wallyford facility in Scotland's Central Belt. It is the only public refuelling station between Sheffield and Aberdeen. |
| 20 | Glasgow City Council Hydrogen Gritters[17] | Glasgow City Council are investigating the potential to use hydrogen within its fleet of heavy vehicles through a grant from Transport Scotland. The first step of this will be to use dual-fuel vehicles. These will act as a steppingstone towards full implementation of their zero-carbon fleet by 2029 ambition. |
| 21 | TECA Fuel Cell[18] | The UKs largest fuel cell is installed at The Event Complex Aberdeen (TECA). It is a 1.4 MW fuel cell, which provides combined cooling, heating and power. The unit reforms biomethane to produce hydrogen, which is then used in the fuel cell. |
| 22 | Methilltoune[19] | Project Methilltoune, in collaboration with project H100, sought to demonstrate that green hydrogen produced using electricity from a wind turbine can be used to supply domestic heating. The project examined how the electricity from a 7 MW wind turbine in Levemouth in Fife, could be used to generate hydrogen from water via electrolysis. This hydrogen would then supply homes which would be converted to using 100% hydrogen in the nearby town of Methil. This would be the first whole system trial of green hydrogen for domestic heating supply in the world. In the first round of the Hydrogen Supply Programme funding, the project received over £400k from BEIS. |
| 23 | HyStorPor20 | The HyStorPor project (Hydrogen Storage in Porous Media) is investigating the possibility of large-scale geological storage of energy in the form of hydrogen. The project is being undertaken by the University of Edinburgh and will:<br>• Undertake controlled laboratory experiments of hydrogen injection into porous rock at subsurface temperatures and pressures to identify and quantify potential chemical reactions.<br>• Assess how effectively hydrogen migrates through water-filled porous media, and how much of the injected hydrogen can actually be recovered from the rock.<br>• Digital computer models of fluid flow adapted from hydrocarbon simulation to scale up from laboratory experiments to an underground storage site.<br>• Ascertain public perception of hydrogen storage underground. |
| 24 | BigHIT[21] | The Building Innovative Green Hydrogen Island Territories (BIG HIT) project is building on the foundations of the Surf 'n' Turf project to create a hydrogen hub in the Orkney Islands bringing together hydrogen production, storage, transportation and utilisation for heat, power and mobility sector. It aims to demonstrate that this approach can be replicated on other locations. Green hydrogen is produced by two PEM electrolysers on Eday (0.5MW) and Shapinsay (1MW) and is then stored in tube trailers for transportation to mainland Orkney. On completion 50 tn of hydrogen will be produced annually for local buildings and transported to Kirkwall for heat and power of harbour buildings, a marina, vessels and a refueling station for road vehicles. |
| 25 | Glasgow Hydrogen Buses[22] | There are plans to introduce hydrogen buses to Glasgow prior to COP 26. This project would see a large scale hydrogen refueling station on the M74 just outside Glasgow using green hydrogen. This station would initially support a small number of buses prior to COP 26. However, there are plans for it to be expanded to service up to 300 buses in the future. |
| 26 | REFlex[23] | The Responsive Flexibility (ReFLEX) project in Orkney will create a smart virtual energy system to monitor generation, grid constraints and energy demand for smart management of the Orkney system. This project will bring together renewable energy assets in the area and expect the following technologies to be introduced during the project: hydrogen fuel cells, smart heating systems, batteries for domestic and non-domestic properties, vehicle to grid charging and electric vehicles. The project has received funding from the Innovate UK via the Industrial Strategy Challenge Fund Prospering from the Energy Revolution fund. |

**Table 1:** Description of the Scottish hydrogen projects (continued)

| NO. | PROJECT NAME | PROJECT DESCRIPTION |
|---|---|---|
| **27** | Promoting Unst Renewable Energy[24] | On the Isle of Unst, Sheltand in 2005, an off-grid community hydrogen system was introduced comprising of a green hydrogen production plant with storage and transport refuelling infrastructure for local vehicles. |
| **28** | The Hydrogen Office[25] | Opened in 2011, a demonstration facility in Methil aimed to promote awareness of renewable energy and energy efficiency by showcasing how potential energy systems could be introduced for offices. The system for the office included a 750 kW wind turbine, 30 kW electrolyser, 5 kW hydrogen boiler, 10 kW hydrogen fuel cell and geothermal source heat pump.<br><br>To support the project, €600,000 was received from the EU's European Regional Development Fund. |
| **29** | Levenmouth Community Energy Project[26] | The aim of the project was to demonstrate how hydrogen storage could be used to resolve challenges associated with the intermittency of renewables for local energy systems; the projected delivered: hydrogen energy storage, compression, fuel cells for energy balancing and refuelling infrastructure for fleet vehicles. The system included a 750 kW wind turbine, 160 kW solar to produce hydrogen via a 270 kW PEM electrolyser. The projected received £4.7 m of funding from the Scottish Government's Local Energy Scotland Challenge Fund. |
| **30** | East Neuk Power to Hydrogen[27] | The project is considering how where excess electricity is constrained, how green hydrogen could be used in a whole energy system across generation, distribution and demand efficiency of both the gas and electricity networks. Hydrogen has been identified as a priority for the site. |
| **31** | MSIP Dundee[28] | Michelin Scotland Innovation Park (MSIP) is a joint venture between Michelin, Scottish Enterprise and Dundee City Council, to transform Michelin's Dundee manufacturing site into an Innovation Parc focused on sustainable mobility and low carbon energy. |
| **32** | Shetland Hub | Shetland Island's Council and Oil and Gas Technology Centre are working on a large-scale energy hub focused on the Shetland Isles. One of the hubs key activities will be to utilise the vast offshore wind resource around the islands to produce green hydrogen. The project is currently in the feasibility phase. |
| **33** | Lewis Hub | The Lewis 100% Green Hydrogen Hub is investigating the potential for a green hydrogen production facility on the Isle of Lewis in the vicinity of Stornoway's proposed deep water port.<br>The Green Hydrogen Hub project has received funding from the Scottish Government's Low Carbon Infrastructure Transition Programme to conduct a feasibility study into the hydrogen production facility and how hydrogen may be used across the Outer Hebrides, the study seeks to investigate the opportunities for hydrogen for heat and transport across the islands as well as the export potential. |
| **34** | Hydrogen Accelerator Programme[29] | The Scottish Government invested £300k in July 2020 in a new hydrogen accelerator programme which will be centered at the University of St Andrews. Drawing on the expertise of the University, and in partnership with institutions across Scotland, the new initiative will propel innovations in hydrogen technology and encourage knowledge-sharing to support transport applications and sustainable mobility. Additionally, the work of the hydrogen accelerator will also support the ambition of phasing out the need for new petrol and diesel cars and vans by 2032. |
| **35** | Aberdeen Hydrogen Hub[30] | The Aberdeen Hydrogen Hub will see significant hydrogen supply and demand growth within and around the city throughout a phased process. Initially this will focus on ensuring a resilient, cost-effective supply of green hydrogen on a commercial basis to support the existing and future transport projects. Phase 2 will see an expansion in demand through trains, trucks and marine applications. Finally, phase 3 will try to further develop the regional hydrogen economy with a focus on skills and supply chain. |
| **36** | Cromarty Firth Hydrogen Hub[31] | Alongside the plans to create a free port in the Cromarty Firth, there are plans to include significant hydrogen deployment at scale through connection to offshore wind. This hydrogen can then be used both locally and to support the hydrogen usage in the rail network around Inverness. |
| **37** | Energy Transition Zone | Opportunity North East will combine Aberdeen and the North East's key energy assets including infrastructure, supply chain, research and development capability and highly skilled workforce to create the Energy Transition Zone. This project aims to develop Aberdeen as a global renewable energy hub, both on and offshore. It will focus on offshore wind, hydrogen and carbon capture, usage and storage. |
| **38** | Outer Hebrides Local Energy Hub | The Outer Hebrides Local Energy Hub developed a collaborative approach to creating a local circular economy on the Isle of Lewis. The project partners, Community Energy Scotland, Pure Energy Centre, The Scottish Salmon Company and Comhairle nan Eilean Siar developed a solution that involved the use of fish waste, alongside household and garden waste, to produce biogas. This biogas powered a combined heat and power system. The excess electrical output from this system was used to produce hydrogen and oxygen both of which are then used in the local economy. |

**Table 1:** Description of the Scottish hydrogen projects (continued)

ARUP

SCOTTISH HYDROGEN
ASSESSMENT PROJECT

# APPENDIX 2

## *Hydrogen Technology*

Scottish Government
Riaghaltas na h-Alba
gov.scot

Scottish Enterprise

HIE

## A2.1 ENERGY TO HYDROGEN CONVERSION FACT CHECKER

Maximum power vs total energy – power and energy are often quoted in MW/GW or GWh/TWh. The former is a measure of instantaneous energy i.e. power, the latter is a measure of total energy over a period. Therefore, a 1 MW wind farm producing at maximum output for 1 hour will produce 1 MWh of energy.

Energy demand - is generally quoted as total annual energy demand i.e. TWh. To provide some context in 2017 Scotland had an annual energy demand of approximately 160 TWh32.

Capacity Factor – most generation plant does not operate at full output continuously. It has down time due to maintenance or because input energy (e.g. wind energy, gas supply) or demand is not at a maximum. Capacity factor is a measure relating maximum theoretical total energy potential against actual.

- Offshore wind farm capacity factors are increasing and the CCC predicted an average capacity factor of 58% for new projects33. As such a 1 GW offshore wind farm operating at a 58% capacity factor over a year will produce 5.1 TWh/annum of electrical energy
- SMR/ATR capacity factors are assumed to be around 86%. As such a 1 GW SMR/ATR operating at a 86% capacity factor over a year will produce 7.5 TWh of hydrogen energy

Hydrogen volumes are either quoted as tonnes or GWh/TWh. One tonne of hydrogen equates to 0.038 GWh of hydrogen.

A blue hydrogen production plant rated at 1 GW will produce significantly more than a 1 GW green hydrogen production plant (7.5TWh vs 3.5TWh in the example illustrated). That is for a number of reasons:

- The capacity factor and utilisation are assumed to be higher for SMR/ATR than the electrolyser. Assuming you match the electrolyser capacity to the wind farm capacity then the electrolyser capacity factor is limited by the input energy from the wind farm. In the natural gas system, it is assumed supply of input energy can more readily be controlled.
- The electrolyser has a lower efficiency than the SMR/ATR (69% vs 80%), and
- Because electrolysers quote their maximum energy capacity at the input of the electrolyser and SMR/ATR quote a value at the output of the SMR/ATR. Therefore, a 1GW electrolyser requires 1GW of electricity input, but a 1GW SMR will need an input of circa 1.3GW of natural gas.

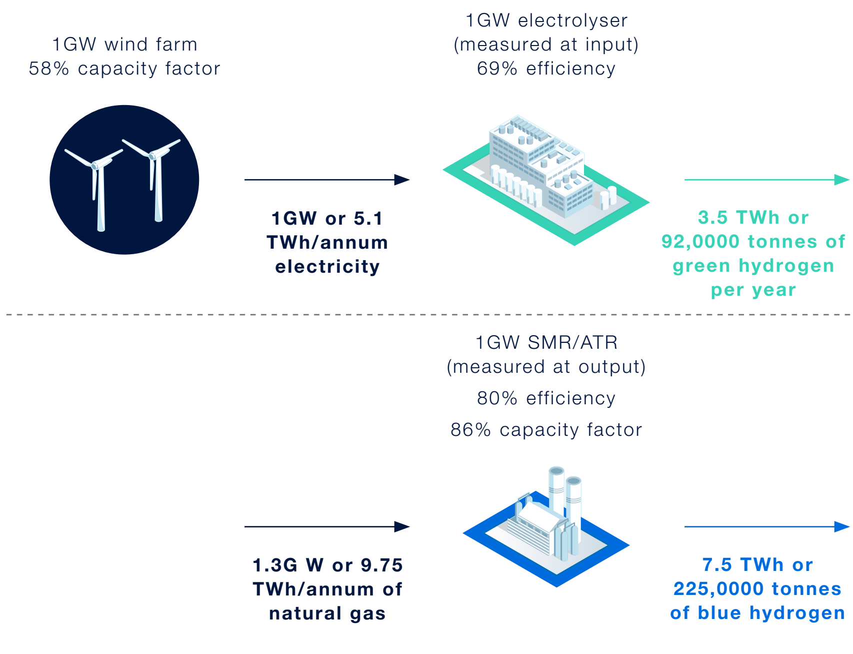


**Figure 1:** Green and blue hydrogen conversion

## A2.2 HYDROGEN TECHNOLOGY DESCRIPTIONS

| | TECHNOLOGY OPTIONS | SUMMARY | EMISSIONS |
|---|---|---|---|
| Production | Fossil Fuel | Hydrogen is stripped from natural gas or coal.<br><br>SMR and Auto Thermal Reforming (ATR) are industrial processes that produce hydrogen from natural gas.<br><br>Gasification of coal produces a variety of calorific gases known as “town gas”, or “coal gas”. This is a mature process but has a high carbon intensity unless carbon capture and storage can be used It is very unlikely that this process will ever be used in Scotland.<br><br>Currently 95% of all hydrogen production worldwide is from fossil fuel as the primary feedstock[34]. | High for coal<br><br>Medium for natural gas<br><br>Low when CCUS is used with coal, and<br><br>Very low when CCUS is used with natural gas |
| | Electrolysis | Electricity is used to split water into hydrogen and oxygen.<br><br>Several different chemistries exist including alkaline, polymer electrolyte membrane (PEM) and solid oxide electrolyser cell (SOEC).<br><br>Currently only 5% of all hydrogen production worldwide comes from electrolysis[34]. | If powered from grid, it depends on grid intensity. The Scottish grid has a very low carbon intensity which is likely to decrease further over time.<br><br>If powered by direct renewable electricity, then it is zero carbon. |
| | Biological | Hydrogen can be produced from both biomass and through direct biological processes.<br><br>Biomass can be gasified in the same way that coal can be.<br><br>Anaerobic digestion can be used to directly produce hydrogen rather than methane by using different microbes. | Depending on the type of biomass can be zero carbon or carbon negative if CCUS is used.<br><br>Direct anaerobic digestion to hydrogen will likely require some form of CCUS. |
| | Carbon Capture and Storage | CCUS generally involves capturing the carbon dioxide that would be emitted during each storage of the hydrogen production process. This carbon dioxide then needs to be stored, likely underground, to avoid the emissions reaching the atmosphere. CCUS is key to allowing hydrogen produced from fossil fuels to exist with net-zero emissions. | This greatly reduces the carbon intensity of producing hydrogen from fossil fuels. Capture rates vary from 90-95%+34 |
| Transportation / Storage | Compressed Gas | Hydrogen can be physically stored as a compressed gas at pressures between 0 bar and 1000 bar and stored in either stainless steel or composite tanks.<br><br>This form of storage can be used for:<br><br>stationary applications at lower pressure where there is sufficient space;<br><br>vehicle applications at higher pressures to extend range.<br><br>The compressed gas can be transported in a tube trailer. | Energy required to compress hydrogen decreases system efficiency and so marginally increases carbon intensity, if that electricity isn’t from a zero carbon source[35] |
| | Liquid | Hydrogen can be cooled and compressed into a liquid, which greatly increased the energy density by volume of hydrogen.<br><br>Liquid Hydrogen – has an energy density of 130 mega joules per kg (MJ/kg) as compared to Kerosene (Jet Fuel) with 43 MJ/kg and lithium ion batteries with 1 MJ/kg. | Substantial energy is required to compress and cool the hydrogen, which decreases system efficiency and so would increase the carbon intensity of the produced hydrogen, if that electricity isn’t from a zero carbon source. |

**Table 2:** Key technologies used within the hydrogen economy

| | TECHNOLOGY OPTIONS | SUMMARY | EMISSIONS |
|---|---|---|---|
| Transportation / Storage | Solid Chemical/Material | Chemical and material storage can take the form of metal hydrides, liquid organic hydrogen compounds. These generally increase storage density by volume compared with compressed gas. | As with compression or liquification, the processes involved would increase the overall carbon intensity of the hydrogen, if that electricity isn't from a zero carbon source. |
| | Gas Grid | Hydrogen can potentially be injected into the current gas grid in places. This can be done either by blending or full transition to a 100% gas grid. | Very little increase in carbon intensity as injection into the gas grid does not necessarily require further compression. |
| | Underground | Gas can be stored at lower pressure in large scale underground storage. This can be in the form of salt caverns or exhausted O&G wells, which are very geographically restricted. Potential new geologies for storing hydrogen are under research and development. | Very little increase in carbon intensity as injection into caverns does not necessarily require additional compression. |
| | Fuel Cell | A fuel cell is an electrochemical device that converts hydrogen and oxygen into electricity and water.<br><br>Like an electrolyser, there are several different chemistries of fuel cell. Within the heat sector, fuel cells are used in combined heat and power (CHP) systems where both electricity and heat are generated. The chemistries most associated with CHP fuel cells are Phosphoric Acid, Molten Carbonate and Solid Oxide. Heat-lead fuel cells generally have a higher tolerance for impurities in the hydrogen supply (99% required).<br><br>These systems achieve high overall system efficiencies of around 90%.<br><br>However, the energy spilt between heat and power depends on the chemistry of the fuel cell. | Carbon intensity depends on type of hydrogen used. |
| Demand – Transport | Fuel Cell | A fuel cell is an electrochemical device that converts hydrogen and oxygen into electricity and water.<br><br>Like an electrolyser, there are several different chemistries of fuel cell. Within the transport sector, almost all fuel cells are PEM systems. These can be used across almost all modes of transport. These fuel cells require very high purity hydrogen (99.97% ISO 14687-2 as a minimum)[37]. Fuel Cells in transport are not CHP and therefore their overall efficiency is around 60-70%. | Carbon intensity depends on type of hydrogen used. |
| | Internal Combustion | Hydrogen can be used as an addition or as a replacement for diesel in an internal combustion engine. Dual fuel conversions could be a key transition technology allowing engines still in operation to be decarbonised. During times of low power draw they will run on 100% hydrogen and only use diesel when extra power is required.<br><br>These systems have comparable efficiencies to those achieved by diesel engines (35-45%). | Carbon intensity depends on type of hydrogen used. Potential for nitrous oxide emissions. |

**Table 2:** Key technologies used within the hydrogen economy (continued)

| | TECHNOLOGY OPTIONS | SUMMARY | EMISSIONS |
|---|---|---|---|
| Transportation / Storage | Solid Chemical/Material | Chemical and material storage can take the form of metal hydrides, liquid organic hydrogen compounds. These generally increase storage density by volume compared with compressed gas. | As with compression or liquification, the processes involved would increase the overall carbon intensity of the hydrogen, if that electricity isn't from a zero carbon source. |
| Demand – Electricity | Fuel Cell | A fuel cell is an electrochemical device that converts hydrogen and oxygen into electricity and water.<br><br>Like an electrolyser, there are several different chemistries of fuel cell. Within the electricity sector, an Alkaline or PEM system is likely to be used in Scotland. The round-trip efficiency of converting electricity to hydrogen and then back to electricity only is around 40-50%.<br><br>Fuel cells can provide benefits to the electricity network such as being flexible, controllable and co-located with demand39 | Carbon intensity depends on type of hydrogen used and the electricity being displaced. For example, using zero carbon wind electricity to displace natural gas generated electricity would see a reduced carbon intensity of the grid. |
| | Gas Turbine | Hydrogen can be used in a gas turbine in the same way that we currently use natural gas. Current gas turbines could only permit a certain percentage of hydrogen within the natural gas flow, sources vary at the moment on what that percentage would be. To run these systems on 100% hydrogen would require modifications to the turbines.<br><br>The efficiency of these turbines is expected to be at least the efficiency of current natural gas turbines. | Carbon intensity depends on type of hydrogen used. Potential for nitrous oxide emissions. |

**Table 2:** Key technologies used within the hydrogen economy (continued)

### A2.2.1 TECHNOLOGY AND COMMERCIAL READINESS

Currently more than 70 mega tonnes (Mt) of hydrogen is produced globally every year[40], mainly for use in chemical production and oil refining. If hydrogen is to become a key energy vector, even to a relatively modest degree, a significant ramp up in production will be required. Understanding of technological and commercial readiness is vital as an enabler to deployment cost reduction and improved operating models, and progress into wide spread commercial deployment.

In Scotland, hydrogen and associated technologies have already been successfully deployed, the majority of which have been demonstration projects. A key challenge of current projects is continued operation at a commercial scale within current economic regulatory frameworks.

Some aspects of hydrogen technology are mature with established costs, others are relatively novel and therefore offer significant opportunities for cost reduction. As use of hydrogen increases economies of scale also offer an opportunity to decrease the unit cost and therefore the price of hydrogen. However, it should be noted that hydrogen is an energy vector created either from fossil fuels or electricity therefore the cost of these inputs will always be a major influence on the hydrogen price.

With its significant renewable energy and natural gas resources there is a significant opportunity for Scotland in hydrogen production. To capitalise on this opportunity, a better understanding of the baseline readiness of hydrogen technologies is required.

### A2.2.1.1 PRODUCTION TECHNOLOGIES

*Grey hydrogen*

Grey hydrogen is hydrogen produced from natural gas or coal without CCUS[38]. Without capturing the carbon, the emissions are released direct to atmosphere. About 95% of hydrogen produced globally is currently produced using fossil fuels without CCUS and is therefore "grey"[38]. The largest proportion of this production uses natural gas[38]. A grey hydrogen production process can be changed into to blue hydrogen production process through the addition of CCUS.

*Blue hydrogen production technologies*

Hydrogen that is produced from fossil fuels but has CCUS included is known as blue hydrogen. In Scotland it is likely that any blue hydrogen will be produced from natural gas taking advantage of Scotland's gas resources and extensive gas infrastructure.

| PRODUCTION TYPE | TECHNOLOGY READINESS | APPROX. TRL[1] |
|---|---|---|
| Steam methane Reforming (SMR) | • Currently the predominant technology in bulk hydrogen production for commercial use[41]<br>• Containerised units commercially available e.g. PRISM Hydrogen Generator produced by Air Products[2]<br>• Emits carbon dioxide, would require CCUS downstream[41]<br>• 70-85% efficiency[42], i.e. a system with an input of 100 MWh of natural gas will produce 70-85 MWh of hydrogen<br>• Estimated 71%-92% of the carbon in SMR can be captured[34] | 9 with no CCUS<br>8 with CCUS |
| Partial Oxidation (POX) | • Commercial production available[9]<br>• Emits carbon dioxide, would require CCUS downstream[9]<br>• 60-75% efficiency[9]<br>• Can operate at smaller scales than SMR[6] | 8 |
| Autothermal Reforming (ATR) | • Steam added to POX process<br>• Emits carbon dioxide, would require CCUS downstream[9]<br>• 60-75% efficiency[9]<br>• 'near term' maturity levels[9], around TRL 8<br>• Can operate at smaller scales than SMR[6] | 8 |
| Coal/Biomass gasification | • Energy intensive process[34]<br>• It is a mature technology with low energy efficiency[34]<br>• Coal plants with CCUS for electricity generation have been demonstrated but not at a commercial scale.<br>• Pre-treatment of biomass adds complexity and cost to the gasification process[34]<br>• Biomass gasification with CCUS could lead to projects being carbon neutral or negative, but this has not been demonstrated yet[34] | 7 |
| Carbon Capture Utilisation and Storage (CCUS) | • $CO_2$ capture technologies exist and are deployed in demonstration or commercial applications[43]<br>• $CO_2$ pipeline or shipping use the same technologies as natural gas, so can be considered mature[44]<br>• $CO_2$ is stored porous geological rock formations and former O&G wells (some similarities with H2 storage – see below). O&G wells are well understood, geological rock formations less so – each rock formation will have unique challenges<br>• According to the Global CCUS institute there are 51 facilities around the world at various stages of development. 19 are fully operational | 9 for use in enhanced oil recovery, 7 for underground storage |

**Table 3:** Blue hydrogen production technologies

**[1]** Technology Readiness Levels (TRL) is a concept used to assess the technical and commercial readiness of technology as they move through their innovation and development cycles. the EU H2020 TRL scale is the one presented and used in this report[125]

Blue hydrogen is only possible alongside the development of CCUS, which captures and then utilise or stores the carbon dioxide by-product. There are a small number of CCUS of projects up and running around the world. Its development though has been hindered by funding issues; in the UK a £1bn CCUS funding competition was finally cancelled in 2015[45]. Recently though CCUS in the UK has received renewed interest and critically funding, with the UK chancellor announcing an £800m CCUS fund for at least two sites at the March 2020 budget[46].

A challenge with CCUS is that it is only viable at large scale and therefore requires large capital investment. A facility therefore needs to be able to capture a large amount of carbon dioxide to be viable. Blue hydrogen could act as enabler of CCUS by producing the quantity required for a CCUS facility to become viable.

Most notably for Scotland in terms of blue hydrogen is Project Acorn which combines hydrogen production and CCUS technologies at the site close to the St Fergus gas terminal in the north east of Scotland.

***Green Hydrogen Production Technologies***

Electrolysis, the process of creating hydrogen from water, has been around for many years, having been first carried out in 1800[47]. Historically, electrolysers have not been widely utilised for hydrogen production due to low historic hydrogen demand and more cost effective alternative methods of hydrogen production. Today it represents less than 5% of total global hydrogen production[38].

The bulk of electrolysis to date has used alkaline electrolysers, a very mature technology. Increasingly PEM electrolysers are seen as a way forward as they have a greater ability to ramp up and ramp down making them better suited to intermittent renewable generation.

Clearly green hydrogen is only green if it uses renewable electricity as its energy source, although there may be circumstances where a back-up grid connection is required as it is more efficient to keep production going than switch-off (potentially the case for alkaline electrolysers)[19]. In Scotland, the largest source of this renewable electricity is wind, including onshore and offshore. Both of which are now mature technologies that has and reduced in cost significantly.

| PRODUCTION TYPE | TECHNOLOGY READINESS | APPROX. TRL |
|---|---|---|
| Alkaline | • Most technologically mature and lowest cost electrolyser[4,19,34,40,48]<br>• First commercially deployed electrolysers, proven track record for operational performance[4].<br>• Has challenges integrating with intermittent renewable energy sources[34]<br>• World's largest alkaline electrolyser plant was167 MW and was operated by Norsk Hydro in Norway (1953-1991)[34] | 9 |
| Polymer Electrolyte Membrane (PEM) | • Rapidly developing, currently relatively immature electrolyser[19,34]<br>• More adapted to fluctuating demand, suited to intermittency of renewable electricity[2,4,48]<br>• Siemens has been operating the world's largest PEM electrolyser system at 6 MW in Mainz since 2015[34]. Shell and ITM Power Ltd are planning to construct a 10 MW electrolyser in Germany[34]<br>• Currently uses platinum, which accounts for bulk of the costs, research is being conducted into alternative materials[19] | 8 |
| Anion Electrolyte Membrane Electrolysis | • Combines an alkaline chemistry system with the benefits of a solid membrane like a PEM.<br>• Limited need for expensive catalysts compared to PEM<br>• Durability remains a concern but the technology is improving<br>• Currently only small scale but in theory could be scaled up | 6 |
| Solid Oxide Electrolyser Cell (SOEC) | • Emerging high temperature technology[48]<br>• Currently only small prototype scale available[48]<br>• Less technically mature than other electrolysers but potential to have the highest efficiencies[34] | 3-5 |

**Table 4:** Green hydrogen production technologies

Electrolysers are generally scalable to whatever size generation they are linked to. Relatively small scale hydrogen production using renewable energy is proven in Scotland with a number of projects as presented in Project Methiltoune[19] and the ITM electrolysers[49,50].

Large scale electrolysers plants could be constructed offshore and directly linked to dedicated offshore wind farms who solely supply the electrolysers either on land at a central location or based offshore. The benefit of this is that the expensive costs of electricity transmission link could be avoided. Alternatively, offshore wind project that have routes to export both gas and electricity could have improved economics through the ability to access multiple revenue streams depending on the preferential market rates.

Large scale offshore production has not yet been proven anywhere in the world, but demonstration projects are underway, for example the Dutch posHydon an offshore wind hydrogen production project[51], and the UK Dolphyn project[4].

### *Grid electrolysis*

Hydrogen can be produced directly via electrolysers supplied with electricity from the grid network. As the electrical grid begins to transition into a low carbon future, the carbon intensity of the hydrogen produced through grid electrolysis reduces. Production of hydrogen through grid electrolysis would be neither ‘green’ nor ‘blue’ at present, as it depends on the status of grid decarbonisation at the time. Whilst this could be a stepping stone into a green hydrogen economy, grid electrolysis is expensive. Both in terms of electricity feedstock cost and the level of grid reinforcements required to move the additional electricity through the grid. Currently, grid electrolysis hydrogen production is roughly three times more expensive than direct connection to a wind farm (green hydrogen production) due to the electricity transmission and distribution costs.

#### *A2.2.1.2 TRANSPORT & STORAGE*

Hydrogen transportation either in gaseous form or liquified form has been carried out for decades and is well established and mature. Storage of hydrogen is established and mature at smaller scale, but expensive on a unit cost basis. Large geological storage offers significantly lower unit costs, though a large capital investment and is less mature.

Storage and transportation of hydrogen in other forms such as ammonia or methlycyclohexane may have cost savings, but more research is required to understand the full chain benefits and drawbacks[52].

| TECHNOLOGIES | DESCRIPTION | APPROX. TRL |
|---|---|---|
| High Pressure Pipelines – Transmission Network | • High pressure hydrogen gas transmission by pipelines well established, with the first constructed in Germany in 1938[53].<br>• As of 2004, there are 900 miles of hydrogen pipelines in the US and 930 miles in Europe[53].<br>• Reuse of steel natural gas pipelines, which make up existing UK transmission network, is a challenge due to propensity for hydrogen embrittlement[38]. | 9 for new build<br>7 for reuse |
| Low Pressure Distribution Network | • Polyethylene (PE) piping has been shown to carry hydrogen with minimal leakage.<br>• A major programme UK distribution networks have been converted from old iron to PE for safety reasons – the Iron Mains replacement programme[54].<br>• Hydrogen could pick up impurities in the pipeline that would make it not suitable for fuel cell use[55]. | 9 for new build<br>7 for reuse |
| Liquid | • Cryogenic hydrogen can be stored and transported in a liquid state. Often this is demanded in industries where purity of hydrogen is high[35].<br>• Used in aerospace applications where high density storage is required[56].<br>• Can be transported by tanker – by road, rail or barge/ship. | 9 |
| Compressed Gaseous or Cooled Gas | • Physical storage of hydrogen by compressing or cooling (or both, known as hybrid) and storing in a tank is tried and tested[35].<br>• Compressed hydrogen storage at 350 bar or 700 bar can be transported through pipelines and via high pressure tube trailers by road[56]. | 9 |
| Solid Chemical/ Material | • Generally material based hydrogen storage methods are still under development[35].<br>• Examples of storage of hydrogen in materials involves metal hydrides, sorption materials and/or chemical hydride[56]. | 4 |
| Underground storage - Caverns, depleted O&G fields and aquifers | • Most cost effective for large scale hydrogen storage[34] as a single facility can store large quantities of hydrogen.<br>• Storage in man-made salt caverns is well proven in use for hydrogen and natural gas[57].<br>• Underground stores have been used for many years for natural gas and crude oil[35].<br>• There is operational experience of hydrogen storage in the USA and Europe where large reservoirs have been used for hydrogen from surplus renewable energy, the most common type used is depleted gas reservoirs[35].<br>• Used widely on industrial scale, but not applicable in all areas as dependent on geographical conditions[58].<br>• TRL around 7-8,[59] but note each underground facility will have its own unique challenges and costs. | 9 salt caverns<br>8 depleted oil fields<br>6 aquifers |
| Bullet containers, Line pack | • Provide well established storage methods that can be easily implemented for small scale storage.<br>• Bullet storage is preferential to line packing, commonly used in the current UK gas network, due to the poor compressibility of hydrogen requiring a significant network length for line packing. | 9 |
| Ammonia and other energy carriers | • Transportation of hydrogen via ammonia is a commercial ready process with high TRL technology available.<br>• 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 or metal hydrides.<br>• Storage of hydrogen can also be in materials such as metal hydrides, sorption materials and/or chemical hydride[56]. | 9 ammonia<br>7 Methlycyclohexane |

**Table 5:** Hydrogen transportation and storage technologies

### A2.2.1.3 END USE APPLICATIONS

Hydrogen is currently used in chemical processes and can also be used to generate energy, either to generate electrical energy through fuel cells, or directly combusted.

| TECHNOLOGIES | DESCRIPTION | APPROX. TRL |
|---|---|---|
| Fuel Cells | • Generate electrical energy from hydrogen with only water as a by-product essentially the opposite of electrolysis.<br>• Fuel cells as a concept is mature and have been used for many years. Different levels of technological maturity depending on the application.<br>• Fuel cell types include PEM, Alkaline, Phosphoric Acid, Molten Carbonate and Solid Oxide 3,26,27 Each have different levels of performance and functionality and require different levels of purity.<br>• Have a wide range of applications in transport through FCVs and stationary fuel cells which can provide power to buildings. | 9 Combined heat and power<br>8 Buses, LGV, cars<br>7 HGV, rail<br>5 Shipping<br>4 Aviation |
| Internal Combustion engines | • Hydrogen can be used as fuel in the internal combustion engine as an alternative to petrol with minor modifications to the engine.<br>• Internal combustion engines adapted to use hydrogen are TRL 8[59].<br>• This conversion can be either 100% to hydrogen or it can be a dual-fuel option. The technology has already been deployed in road vehicles and is currently being testing in the marine environment.<br>• Other conversions are currently much lower TRL, for example using liquid hydrogen as a replacement for kerosene in aviation. | 9 HGV<br>6 Shipping, Aviation |
| Combustion heating | • Hydrogen can burn to provide heating at from industrial down to domestic scale – a like for like replacement for fossil fuels.<br>• Approximately 4,300 relevant industrial heating equipment pieces that operate on natural gas that could be converted to hydrogen[36].<br>• There are many different technology types that could be adapted to utilise hydrogen for the application of industrial heating including boilers (TRL 7), direct dryers (TRL4), kilns (TRL4), Conventional Furnace (TRL5), glass furnace (4), gas turbines (TRL8), gas engine (TRL 4)[36].<br>• Hydrogen options considered to have potential for large scale decarbonisation of heat for homes hydrogen boilers, (TRL 7), cookers and fireplaces. None of these have yet been deployed widely yet[60]. | 9 industrial current use<br>4-7 industry fuel switch<br>7 domestic |
| Hydrogen gas Turbines for power generation | • Gas turbines using natural gas are well developed, these can be converted to use hydrogen.<br>• Gas turbines are a high TRL and using hydrogen as the feedstock is the equivalent of ‘business as usual’ for electricity generated by hydrogen39.<br>• In terms of large scale gas turbines, the TRL is around 8[59]. | 8 |

**Table 6:** End use technologies

Different applications are in different stages of technical and most critically commercial deployment, see Table 7 below for a summary of different applications.

| SECTOR | END USE | HOW IT CAN BE USED | TECHNOLOGY READINESS | COMMERCIAL DEPLOYMENT |
|---|---|---|---|---|
| Industry | Existing industrial processes and feedstock. feedstock | Petroleum refining and chemical production including ammonia and methanol currently accounts for 90% of hydrogen uses today[62] | Mature technology – have been used within industry for decades | Already using grey hydrogen likely to be one of the first areas to deploy blue or green hydrogen |
| | Industrial heating | Replace fossil fuels in industrial heating, particularly for medium (100° to 400°) to high grade heating 400° | Technology approaching readiness. Still need to understand details of hydrogen chemical reactions when fuel switching. | Commercial deployment is driven by reducing cost of hydrogen production and delivery |
| | Power generation | Replaces natural gas and coal in thermal generation | Feasibility studies are underway with projects due to be demonstrate from early 2020s | Commercial deployment is driven by reducing cost of hydrogen production |
| Transport | Road fleets | Buses, taxis, delivery vehicles, industrial vehicles e.g. forklifts. | Hydrogen buses and taxis have been deployed in regional clusters and are increasing in deployment | Small scale industrial vehicles are expected to be commercial in the early 2020s. Passenger cars, buses and material handling vehicles are close to the early stages of full commercialisation in the mid-2020s, with usage range extending following this |
| | Heavy long-distance vehicles | Heavy goods vehicles, vans, long distance coaches | Initial prototypes have been developed, larger-scale roll-out is yet to begin | Likely to be commercially deployable in the mid-2020s with longer distance vehicles following afterwards |
| | Personal transport | Personal vehicles | Hydrogen vehicles are being brought to market by manufacturers, further market development expected in mid-2020s | Long range vehicles from early 2030s with short range vehicles following subsequently |
| | Trains | City / commuter trains and long-distance regional trains | Currently only operational in small numbers, with testing in UK, Germany and Netherlands | Expected to be commercially deployed from the early 2020s |
| | Aviation | Short and long-haul aviation | Immature, currently being trialed for short-haul airplanes (see project HyFlyer[15]) | Expected to be commercially deployed from the early 2030s |
| | Shipping | Shipping for both commercial and non-commercial activities such as ferries and RoPax | Have been around in small numbers since early '00s, however no real commercial viability yet, technology remains is in early design /feasibility.<br><br>Trials of dual-fuel ferries currently ongoing in Orkney (HyDime)[13] | Expected to be commercially deployable in the early 2030s for regional and roll on/roll off ferries and passenger ferries |

**Table 7:** Summary of different end uses of hydrogen. Information Source:[61]

| SECTOR | END USE | HOW IT CAN BE USED | TECHNOLOGY READINESS | COMMERCIAL DEPLOYMENT |
|---|---|---|---|---|
| Buildings | Heat in buildings | Heat for commercial and domestic buildings, includes boilers, cookers and fireplaces | Hydrogen blending of up to 20% is being trailed now.<br><br>The development and safety case of 100% hydrogen appliances is being investigated (Hy4Heat programme[36,63]) Demonstration appliances have been constructed | Blending could happen by early 2020s<br><br>100% hydrogen conversion of buildings could likely be deployed from 2030s but is tied to decisions on conversion of gas networks to hydrogen |
| | Fuel cells Micro combined heat & power | Generates electricity locally and then recovers and uses the by-product heat for hot water, space heating and power | Relatively mature, with several products currently on the market in Europe[64] | Commercial deployment will be driven by reducing hydrogen production costs |

**Table 7:** Summary of different end uses of hydrogen. Information Source:[61] (continued)

Finally, hydrogen purity is also an important factor to consider, some hydrogen fuel cells require very pure hydrogen (99.99%). 'Blue' hydrogen is not this pure so will have to be 'cleaned' before it can be used in these fuel cells which requires additional energy and cost. Similarly, any hydrogen put into a pipe network or stored in geological storage (particularly former O&G fields) will pick up impurities and will potentially need to be cleaned at the point of use. This will need to be considered when thinking about hydrogen supply chains.

## A2.3 INNOVATION AND ACADEMIA

| UNIVERSITY | KEY RESEARCH AREAS, GROUPS AND INSTITUTES |
|---|---|
| University of Edinburgh | Energy Storage and Carbon Capture Group<br>Aims to develop cost competitive technologies including storage technologies and their integration into the wider energy system. This includes hydrogen storage and conversion to chemicals (especially process simulation for $CO_2$ utilisation), as well as energy grids that incorporate hydrogen, from small scale and island to large scale geological storage.<br><br>HyStorPor[20]<br>£1.4M studying underground hydrogen storage<br><br>UKERC<br>Marine to hydrogen research and whole energy system modelling |
| University of St Andrews | HySEAS[10] and Hydrogen Accelerator[29]<br>Project management through School of Chemistry<br><br>Solid oxide fuel cell<br>World leading fundamental research in the production of these systems |
| Heriot Watt University | Research Centre for Carbon Solutions<br>Research in carbon capture technology, flow measurement and transport technology, $CO_2$ utilisation and storage, renewable energy resources and energy and sustainability.<br><br>Industrial Decarbonisation Research and Innovation Centre<br>Funded by the Industrial Strategy Challenge Fund to decarbonise industrial clusters. The centre was recently established and will work with the UK's industrial clusters to develop technologies for industrial decarbonisation, specific technologies and programmes are not yet established but CCUS and hydrogen are likely to be tools for industrial decarbonisation. |
| University of Strathclyde | Centre for Energy Policy<br>Research covers the full energy supply chain and include the economic impacts of changes in the system, research investigates the whole energy system, recent publications have covered the macroeconomics of CCUS.<br><br>Energy Systems Research Unit<br>Development of new technologies and methods for energy utilisation and supply. The unit has developed computational tools to aid in the development of energy systems, areas of expertise include low carbon heating and cooling and hydrogen energy systems.<br><br>Power Networks Demonstration Centre<br>Investigating hydrogen production into their simulations of the electricity network.<br>Research in hydrogen powered vessels as part of the Sustainable Shipping research programme. |
| University of Glasgow | Improved Electrolysis<br>Research into solid state electrocatalysts for hydrogen generation and $CO_2$ storage. |
| University of Highlands and Islands (UHI) | Lewes Castle College<br>UHI has created a small scale hydrogen laboratory to investigate the interaction between an electrolyser and electrical systems. There is also a programme of hydrogen related training, research and development. |
| Edinburgh Napier University | Scottish Energy Centre<br>Focuses on the development of renewable energy systems and sustainable design om construction. Research into developing low and zero carbon technologies including fuel cells.<br><br>Hydrogen lab<br>Small hydrogen laboratory with an electrolyser, a photo-voltaic façade, two wind turbines and a small experimental solid oxide fuel cell stack. |
| University of Aberdeen | Schools Hydrogen Challenge<br>Supporting skills development in high school aged pupils |
| Robert Gordon University | Hydrogen vehicles<br>Operating a small hydrogen vehicle fleet. |

**Table 8:** Innovation and academia.

ARUP

SCOTTISH HYDROGEN
ASSESSMENT PROJECT

# APPENDIX 3

## *Scenarios*

Scottish Government
Riaghaltas na h-Alba
gov.scot

Scottish Enterprise

HIE

## A3.1 EXPLORING SCENARIOS

A key part of the assessment is the creation of possible future scenarios for hydrogen in Scotland. The purpose of using scenario analysis was to explore at a high level with a number of key stakeholders, the range of roles that hydrogen could play in a future energy economy. The intention was not to create accurate predictions of the future, but to show a range of different possibilities for how hydrogen could be used, produced and transported in Scotland and then what impact this would have on the Scottish economy.

The scenarios were developed over two stages; from an initial round of stakeholder engagement a 'long list' of potential future scenarios were developed, see Figure 2. These scenarios provide outlines of roles that hydrogen could play in Scotland in 2045. They were not intended to be fully formed scenarios with timelines through to 2045 rather they were intended to show the full range of roles that hydrogen could play in the economy. This could range from small roles in particular sectors or regions to large roles across a number of different sectors. In reality hydrogen usage would not be so polarised, for example it may be considered unlikely that hydrogen will be used only in industry and power generation and not used at all in other sectors.

Setting out this long list allowed for the next stage – developing a short list of more rounded scenarios.

| | HYDROGEN EXPORTER NOT USER | LIMITED HYDROGEN IN SOME SECTORS | SMALL, FRIENDLY LOCAL HYDROGEN | BIG GREEN HYDROGEN – FOR TRANSPORT | FULL GAS NETWORK CONVERSION | ONLY THE BIG PLAYERS - INDUSTRY AND POWER | LARGE CLUSTER – CITY OR REGIONAL CLUSTERS | FULL HYDROGEN EVERYWHERE |
|---|---|---|---|---|---|---|---|---|
| *Scenario Synopsis* | Scotland becomes a centre for hydrogen production in Europe, exporting hydrogen across the rest of Europe and possibly beyond. | Hydrogen is used throughout Scotland in those sectors or facilities where hydrogen is the only or the most efficient and cost-effective way of decarbonising. | Hydrogen is produced and used in small clusters where there are production advantages and/or where other forms of decarbonisation are difficult. But not elsewhere. | Entirely green hydrogen. Produced at large scale is used in hydrogen fuel cells which are primarily used in the transport sector. | Scotland's gas network is fully converted to 100% hydrogen. All domestic and industry currently connected to the gas grid are switched to hydrogen. | Hydrogen is produced at scale either through Blue and Green means and used extensively in industry and power generation. It is not used for any smaller applications. | Hydrogen is used extensively in a few large clusters - wholes cities and/or regions cities in Scotland but hardly at all in the rest of the country. | Hydrogen production in Scotland is maximised and is used all possible sectors as much as possible. This is used all sectors as much as possible. |
| *Hydrogen Production* | Mass offshore wind hydrogen and blue hydrogen production for export. | Blue hydrogen for industry and green hydrogen for transport. | Green hydrogen production primarily using smaller local sources. | All hydrogen is green primarily produced at scale using large offshore wind. | Hydrogen is produced at scale - both blue and green hydrogen. | Blue hydrogen is the primary production method with some green. | Blue or green hydrogen production depending on cluster location. | Maximum hydrogen production using all available technologies. |
| *End Use* (INDUSTRY AND POWER GENERATION; TRANSPORT; HEAT) | Used a small amount in industry and niche transport sectors that are located near to ports. | Hydrogen end usage includes industrial feedstock, 'Back to base' transport fleets and large long distance, heavy vehicles. | Hydrogen used for multiple purposes within each small cluster - heat, local transport fleets and smaller scale industrial. | Hydrogen used for multiple purposes within each small cluster - heat, local transport fleets and smaller scale industrial. | Hydrogen has a major role in domestic & commercial heating and industry & power generation. Not used in transport. | Large industrial users switch to hydrogen but there is limited hydrogen use in other sectors. | Within each cluster it is used extensively across all sectors. Not used outside of the large clusters. | Hydrogen has a large role in each of the sectors at each level. |
| *Import / Export* | Large scale export to Europe/Worldwide. | No export/import. | No export/import. | Some export to England via transmission network. | Some export to England via transmission network. | Some export to England via transmission network and some European shipping. | Potential to export or import hydrogen from/ into each cluster. | Some hydrogen import. |
| *Transmission, Distribution and Storage* | Hydrogen is located near ports and/or transported to ports via high pressure pipelines from where it is transported around Europe/the world. | Hydrogen for industry uses co-located blue hydrogen production supplied by natural gas transmission. Tanker network supplies the green hydrogen to refuelling points. | Small local hydrogen distribution network within the cluster. Some road tankers supply refuelling points within the cluster. | Mostly transported by tankers to refuelling stations around Scotland. Pipelines could be built from production plants to regional distribution centres. | Today's gas network will remain with upgrades and replacements. Green hydrogen will be connected at distribution level and CCUS network will be established. | A hydrogen transmission network transports hydrogen from production locations to the large users. There is no small level distribution network or tanker network. | Gas distribution networks within clusters are converted to hydrogen. Tanker transporting hydrogen to refuelling centres. | The whole gas networks is converted to hydrogen with new hydrogen pipelines where necessary. Tanker network transports hydrogen to refuelling centres. |

**Figure 2:** TLong list of scenarios.

### A3.1.1 SCENARIO DESCRIPTIONS

#### A3.1.1.1 HYDROGEN EXPORTER – NOT USER

Scotland becomes a centre for hydrogen production in Europe, exporting hydrogen across the rest of Europe and even beyond.

| | |
|---|---|
| End Use | Hydrogen plays a very minor role in Scotland's domestic energy scene; only parts of the economy that cannot or are very difficult to decarbonise by any other means use hydrogen. This includes the chemical production industry, a limited amount in industrial feedstock and niche industrial transport fleets such as forklift trucks in warehouses and ports. |
| Hydrogen Production | Hydrogen production becomes a major industry in Scotland, with the vast majority of hydrogen produced exported. In 2045 production is both blue and green with green a larger and growing percentage. Green hydrogen is primarily produced at large scale offshore on floating platforms co-located with large offshore wind farms which produce electricity only for the electrolysers. |
| Transmission, Distribution and Storage | Hydrogen production is located near to ports or piped to shore from the offshore production facilities to ports. From here the hydrogen is exported to Europe and around the globe by ship. At least one high pressure hydrogen pipeline connects Scottish hydrogen production to England. Hydrogen storage facilities around the ports are used to store hydrogen prior to export. Any domestic hydrogen usage in Scotland is located near to these port facilities and connected by short pipelines (for industrial usage) or by road tankers (for usage in transport). Other than this there is no hydrogen network in Scotland. |
| Economic Impact | **GVA potential:** High<br><br>**Job creation:** High, all skills levels<br><br>It is anticipated that the economic benefits resulting from this scenario would be considerable. The absolute size of hydrogen production is itself considerable and the scenario would naturally be expected to deliver more value than other less ambitious scenarios. By seeking out high value export markets, there is an opportunity to maximise the economic benefit of the green hydrogen potential in Scotland.<br><br>In addition, the concentrated focus on (primarily) offshore wind generation coupled with the massive offshore and onshore electrolyser capacity could be expected to increase the overall impact by reaching a 'tipping point' of expertise in systems integration, positioning Scotland as a world leader in this domain. The scenario leverages existing skills and capabilities in Scotland associated with the offshore oil and gas industry, e.g. offshore logistics and pipeline construction.<br><br>Significant job creation could be anticipated across a wide range of skill levels and across the regions, focused perhaps on the east coast and Aberdeen in particular but including the Islands and rural as well.<br><br>The lack of any domestic hydrogen use limits the potential economic value resulting from, e.g. bus manufacture. |

### *A3.1.1.2 LIMITED HYDROGEN – IN SOME SECTORS*

Hydrogen is used in those sectors or facilities where hydrogen is the only or the most efficient and most cost-effective way of decarbonising.

| | |
|---|---|
| End Usage | Hydrogen is used across Scotland in a limited number of situations where the alternative decarbonisation route is too expensive and/or impractical. It is used in industrial feedstock in some industries where CCUS is too difficult. Also, it is used as a more efficient alternative to electric vehicles in some 'back to base' local transport fleets for example local buses, delivery vehicles, taxis and long distance intercity transport coaches, HGVs and non electrified rail. Note hydrogen is not exclusively used in these sectors, hydrogen is only used where it is deemed more efficient than EVs. Hydrogen is not used in domestic or commercial heating. |
| Production | In this scenario, production is dependent on the sector in which it is used; hydrogen for industrial usage is primarily produced using blue hydrogen from natural gas either from the North Sea or imported LNG facilities. Green hydrogen is used in transport fleets, produced at a local level using relatively small scale onshore wind, solar and tidal. |
| Transmission, Distribution and Storage | Natural gas still plays a large role in the Scottish energy sector, along with carbon capture and storage. The natural gas transmission system of today has been maintained and is feeding heavy industry directly or the blue hydrogen SMR facilities. A parallel carbon network is built, taking the carbon away from its point of use to the CCUS stores in the North Sea. The high pressure natural gas distribution network may be maintained but most of the distribution network is decommissioned as heat is electrified. Green hydrogen production is located near to demand therefore there is a limited road based hydrogen refuelling network. |
| Economic Impact | **GVA potential:** Low<br><br>**Job creation:** Low, low- to mid-skill level<br><br>The modest ambition of this scenario naturally limits the maximum value creation potential it presents. The absolute size of the opportunity is therefore relatively limited.<br><br>In addition, activity is spread between multiple sectors of the economy and as a result it is difficult to see how any one sector could reach critical mass. This further limits the value creation potential as sectors fail to benefit from factors such as learning by doing and industrialisation.<br><br>However, some opportunities exist around existing skills bases such as bus manufacture at ADL where manufacturing cost reductions can be realised even at relatively small volumes.<br><br>Some service based opportunities exist around the deployment and operation of hydrogen refuelling stations, for example, as well as in operations and maintenance of transport fleets. This points to most of the jobs being in the low- to mid-skill level, with relatively few high skill jobs resulting. |

### *A3.1.1.3 SMALL, LOCAL HYDROGEN*

Hydrogen is produced and used in small clusters where there are production advantages and/or where other forms of decarbonisation are difficult.

| | |
|---|---|
| End Usage | Hydrogen is used across a variety of sectors within small clusters. It is used in local buses, taxis, delivery vehicles and other local areas. Local fuel stations will also offer hydrogen for personal vehicles including agricultural vehicles and machinery. Hydrogen is used for domestic and local heating and in local industry. |
| Production | Hydrogen is produced at relatively small scale using small electrolyser facilities linked to small scale renewable energy including onshore wind, offshore wind, solar and tidal. All the hydrogen produced is consumed within close proximity to where it is produced. |
| Transmission, Distribution and Storage | Production is located near to its point of use, therefore there is no requirement for a national hydrogen transmission system. Small discrete local distribution networks operate, connecting domestic and commercial heating and small industry. Within each cluster a small road tanker network operates supplying hydrogen for transport refuelling points. Storage facilities operate to ensure a steady supply of hydrogen for the cluster all year round. |
| Economic Impact | **GVA potential:** Small<br><br>**Job creation:** Small, low- to mid-skill levels<br><br>In this scenario we would expect the technology solutions that are deployed to be quite heterogenous with bespoke solutions designed to meet the needs of individual small clusters. This scenario therefore suffers from many of the same disadvantages as the “Limited Hydrogen” scenario with regards to both absolute size and failure to achieve critical mass.<br><br>Benefits would be similar to those identified for “Limited Hydrogen” but these would arguably be smaller still given the very localised nature of the developments. |

### A3.1.1.4 BIG GREEN HYDROGEN – FOR TRANSPORT

Entirely green hydrogen is mass produced primally in large offshore platforms linked to offshore wind farms. This hydrogen is used exclusively in hydrogen fuel cells which are primarily used in the transport sector which becomes a largely hydrogen powered sector.

| | |
|---|---|
| End Usage | Hydrogen plays a major role in the transport sector in Scotland, being the main replacement for petrol and diesel. Fuel cells are also used in some strategic places for electricity generation. Hydrogen is not used in any other sectors. Some of the hydrogen is exported to England by pipeline. |
| Production | In this scenario all hydrogen is green and is primarily produced from large offshore or coastal electrolyser plants using renewable energy from offshore wind farms. The electricity from these wind farms is exclusively used to produce hydrogen. Some hydrogen is also produced from tidal resources. |
| Transmission, Distribution and Storage | In this scenario distribution of hydrogen effectively mirrors the existing petrol and diesel supply chain. Hydrogen will be transported around the country from major production sites to refuelling stations by road and rail tanker. Hydrogen pipelines transport hydrogen from production sites, much of which is offshore, to distribution centres from where it will be delivered to refuelling stations via tankers.<br><br>Aside from one or two strategic pipelines that may fit with the strategy above and one or two export pipelines to England, the gas distribution network is largely decommissioned. Some of the natural gas network remains carrying natural gas for industry, a parallel $CO_2$ network is required to take the captured $CO_2$ to storage sites. |
| Economic Impact | **GVA potential:** Mid-level<br><br>**Job creation:** High, all skill levels<br><br>This scenario could be expected to realise many of the same benefits as the “Hydrogen Exporter” scenario but would likely be smaller in absolute scale. There is a question mark over whether critical mass could be reached in offshore wind-electrolyser integration but if this could be achieved then the benefits would be considerable.<br><br>While the benefit from green hydrogen production may be smaller than if exported, more benefits could be expected to accrue to activities such as bus manufacture. There would also be more HRS roll-out and more opportunities in operations and maintenance in the transport sector.<br><br>The lack of any established fuel cell manufacturing in Scotland limits the value potential and it is highly unlikely that the size of the opportunity would be significant enough to attract foreign manufacturers to invest in establishing manufacturing or assembly activities in Scotland. There exists reasonably strong integration skills in the fuel cell domain which could be strengthened as a result of the increased demand for hydrogen demand. |

#### *A3.1.1.5 FULL GAS NETWORK CONVERSION*

Scotland's gas network is fully converted to 100% hydrogen. Most domestic, commercial and industrial currently connected to the gas grid are switched to hydrogen. The hydrogen is manufactured from both blue and green sources.

| | |
|---|---|
| End Usage | A large proportion of domestic and commercial heating and cooking is hydrogen. Industrial customers connected to the grid (transmission and distribution) are switched to hydrogen, including power stations currently connected to the transmission grid. Some transport fleets are run using hydrogen, sourced from the network and cleaned to allow it to be used in fuel cells, however the majority of transport does not use hydrogen. |
| Production | Given the large amount of hydrogen required, both blue and green hydrogen production plays a significant role in 2045. Blue hydrogen is produced using North Sea natural gas and imported LNG with the CCUS in storage facilities of the eastern coast of Scotland.<br><br>Blue hydrogen has provided the bulk of hydrogen production thus far, however by 2045, over 50% of production is green using Scotland's abundant wind and tidal resources. This proportion of green is expected to grow until eventually it is 100% of production – expected sometime in the 2050s. |
| Transmission, Distribution and Storage | The gas distribution network operates largely as today, with hydrogen replacing natural gas. The transmission network will either have been upgraded or replaced. Hydrogen storage is particularly important in this scenario given the large differential in summer and winter heating demand, large scale geological storage using geological caverns are used to store hydrogen in summer for use over the winter. |
| Economic Impact | **GVA potential:** Mid-level<br><br>**Job creation:** High, mid-skill level<br><br>In common with "Big Green", this scenario could be expected to realise many of the same benefits as the "Hydrogen Exporter" scenario but would likely be smaller in absolute scale. There is a greater question mark over whether critical mass could be reached in offshore wind electrolyser integration since this scenario postulates a mix of both blue and green hydrogen.<br><br>There will be limited opportunities to capitalise on skills in areas like vehicle OEM design and production, but there would be considerable activity in gas network conversion and / or installation. Scotland does not have an indigenous boiler or fuel cell manufacturer and would be sub-scale for attracting a foreign one, limiting the economic benefits.<br><br>Job creation could be extensive, especially during the construction / conversion phase but these may be in lower skill levels. In common with "Exporter" and "Big Green", high level skills around renewable-electrolyser integration could be anticipated. The focus on the gas network may reduce the opportunities for regional job creation especially in rural and islands locations. |

### A3.1.1.6 ONLY THE PLAYERS – INDUSTRY AND POWER GENERATION

Hydrogen is produced at scale either through blue and green means and transported around the country using hydrogen transmission network. It is not used for any other smaller applications.

| | |
|---|---|
| End Usage | Hydrogen is only used by very large energy users such as industrial feedstock (steel works, cement production etc) and power generators.<br><br>Hydrogen is used significantly in power generation in hydrogen CCGTs, providing a significant amount of power generation in Scotland and help to balance the system which is otherwise dependent on renewables. In effect hydrogen in this scenario is used as an energy storage for the power grid, being produced at times of energy surplus and then being used to generate at other times. |
| Production | Blue hydrogen is manufactured using the remaining North Sea natural gas and imported LNG. The $CO_2$ is then captured and stored in CCUS facilities of the eastern coast of Scotland.<br><br>Blue hydrogen has provided the bulk of hydrogen production thus far, however by 2045, a growing proportion of production is green using Scotland's abundant wind and tidal resources. This proportion of green is expected to grow until eventually it is 100% of production – expected sometime in the 2060s. |
| Transmission, Distribution and Storage | Only a high pressure transmission network is required in this scenario. This network will be largely new rather than converted existing gas transmission though may follow similar routes. This network will be limited as possible users will be located near hydrogen production centres. At least one transmission line connects Scotland to Northern England where Scottish hydrogen is used in heavy industry and power production. |
| Economic Impact | **GVA potential:** Mid- to low-level<br><br>**Job creation:** Mid-level, mid-skill level<br><br>The benefits and disadvantages of this scenario mirror those in the "Full Gas Network" scenario but would be a smaller absolute size. |

### A3.1.1.7 LARGE CLUSTERS – CITY OR REGIONAL CLUSTERS

Hydrogen used in a small number (3-4) of large clusters which are whole cities or regions. Within these clusters hydrogen is used extensively across all sectors, but hydrogen is not used outside the clusters.

| | |
|---|---|
| End Usage | Hydrogen is used extensively across all sectors; heat, transport, industry and power generation, within the clusters. For transport, it is used in personal, commercial and fleet vehicles such as local buses, train services, taxis, delivery vehicles and other local fleets. Long distance intercity travel does not use hydrogen as it is prevented by its unavailability outside of the cluster. Hydrogen is used for domestic and local heating and in local industry and potential also local power generation. |
| Production | The production will depend on the location of the cluster in relation to Scotland's natural resources. At least one cluster will be based around blue hydrogen using North Sea gas and/or imported LNG. By 2045 this has started to be replaced with green hydrogen produced by offshore wind farms. Other clusters could use large scale green hydrogen from the start, though these clusters would likely start later. |
| Transmission, Distribution and Storage | Within the clusters the gas distribution network is maintained and converted to hydrogen but decommissioned elsewhere. A limited number of high pressure pipelines transport the hydrogen from large scale production to the clusters. A road tanker network is used to supply refuelling stations within the cluster from a central distribution point. |
| Economic Impact | **GVA potential:** Mid-level<br><br>**Job creation:** Mid-level, all skills levels<br><br>This scenario would resemble "Full Hydrogen" and could potentially offer most of the benefits to the energy system with a smaller level of concentrated investment. For example, "Clusters" might allow conversion of the transport fleet to 80% of the level envisaged in the "Maximum Hydrogen" scenario but require fewer investments in refuelling infrastructure owing to its tighter geographical location.<br><br>Both economic activity and job creation will be, by definition, more localised and the opportunities for rural and island locations may therefore be more limited. |

#### A3.1.1.8 FULL HYDROGEN

Scotland produces as much hydrogen as it possibly can and this is used extensively domestically across all sectors and geographies.

| | |
|---|---|
| End Usage | In this scenario hydrogen becomes the main energy vector, and is used widely across industry, transport and heating. Other decarbonisation forms are only used when it is not possible or impractical to use hydrogen. Hydrogen is also used in power generation allowing for the complete decarbonisation of power. |
| Production | Scotland maximises all its resources to produce as much hydrogen as it can. Blue hydrogen plays a dominant role early on using North Sea gas to produce hydrogen with the carbon stored in large scale CCUS in the North Sea. By 2045 green hydrogen is produced from a variety of sources, incl. renewable onshore and offshore wind, tidal and solar with varying production scales. In 2045 production is around 50/50 between blue and green but green is expected to become the sole means of production by the 2060s. |
| Transmission, Distribution and Storage | A full gas network system is maintained, distribution networks have been converted to hydrogen, some small scale distribution renewable generation is directly connected at this level.  A new hydrogen transmission high pressure network is built to transport large volumes of hydrogen from centres of production to demand centres. These pipelines feed, large users, distribution networks and refuelling distribution centres from where trucks are used to supply hydrogen for transport refuelling stations. In this scenario hydrogen may be imported into Scotland using port facilities from countries where hydrogen is produced on mass at low cost. |
| Economic Impact | **GVA potential:** High<br><br>**Job creation:** High, all skills levels<br><br>The scenario should deliver strong systems integration capability around the deployment of offshore green hydrogen while at the same time strengthening the skills around transport infrastructure. However, the presence of both blue and green hydrogen may prevent Scotland from attaining the tipping point in offshore green. This may be countered by strong development in other sectors such as bus manufacture.<br><br>Job creation is likely to be significant and spread across skill levels and the regions. |

## A3.2 CREATING THE FINAL THREE SCENARIOS

Following the identification of the long list of scenarios, three main scenarios were identified and developed with stakeholders. These three scenarios encompass elements of more than one of the long listed scenarios.

Each scenario makes different assumptions on what happens to hydrogen internationally and therefore how that impacts on how hydrogen is used in Scotland. Some of these assumptions are deliberately bold as the intention was to avoid scenarios that are too similar to each other and therefore are not explore a full range of outcomes. Each scenario has its own challenges and difficulties that would need to be overcome if it were to become a reality.

In each scenario it is assumed that net-zero is achieved, the scenarios envisage the different roles hydrogen will play. In each scenario a proportion of energy demand, in TWh, in each sector is met by hydrogen and in some scenarios some of the hydrogen produced is exported. Each scenario envisages different amounts of blue and green production.

For green each scenario assumes that a proportion hydrogen is made onshore at small to medium scale and another proportion is made at large scale using offshore wind.

The scenarios are designed to reflect the views of stakeholders and in literature. In some sectors the scenarios are similar where nearly all stakeholders were in agreement, e.g. the use of hydrogen in fleet transport and the use of small-medium green production. In some they are quite different to reflect differences in views such as use of hydrogen in the gas network and the role of blue hydrogen.

### A3.2.1 SCENARIO A: HYDROGEN ECONOMY

#### A3.2.1.1 THE DEVELOPMENT OF THIS SCENARIO

This scenario is developed from the long listed scenarios where hydrogen is extensively used across Scotland. The central logic of this scenario is that hydrogen is the primary means of decarbonising Scotland's economy. It is assumed that hydrogen develops in a similar way across the UK.

This scenario explores using hydrogen in all sectors where stakeholders and existing literature feel there was a good case for it to be used in Scotland. Where stakeholders felt it was unlikely that hydrogen would be used it is not used in this scenario. For example, in transport hydrogen is used extensively in heavy and fleet vehicles in this scenario but less so in smaller and personal vehicles where most stakeholders and literature are more sceptical about hydrogen's potential to in this market.

Where there is a decision to be made, such as whether to use hydrogen at scale in heating and therefore in the distribution network, this scenario imagines that a decision has been made in favour of using hydrogen. This is also a national scale scenario where hydrogen is used across all of Scotland, if there is a good case for its use but with some differences to how it is used in different regions.

This scenario reflects the view of many stakeholders, that blue hydrogen is used initially to produce hydrogen, but is eventually displaced by green. The use of blue is also connected to the types of demand envisaged with hydrogen used more in the network as a combustion fuel, in heating and industry. Here scale of production is more important than purity, which is needed to use in fuel cells in transport. This scenario is the most ambitious in terms of the build-up rate of hydrogen produced, but by 2045 Scenario B: Green Export imagines higher overall production. This reflects the need for hydrogen to be used in heating decarbonisation and that blue hydrogen is used to get to scale of production relatively quickly.

#### A3.2.1.2 SHORT TERM – 2025

***Demand***

By 2025 a full hydrogen economy is still far away but hydrogen is being used at some scale, though still modest in comparison to the entire energy system. Just under 2TWh compared to an overall Scottish energy demand of 160TWh in 2017.

The majority of hydrogen production (over 75%) comes from the blue hydrogen facility in Aberdeen. The hydrogen from this facility is primarily injected into the gas network and blended with natural gas (around 2% by volume[2]), reducing slightly the $CO_2$ emissions of gas use. Given the small percentage, existing gas residential, commercial or industrial appliances can continue to be used[68,117].

Hydrogen is beginning to be used more in transport, driven by conversion of public sector fleets or in fleets the public sector has some control over. Hydrogen is used particularly in buses and small numbers of hydrogen FCVs are used by councils and other public sector organisations. A small number of hydrogen fuelled HGVs are on Scottish roads and initial demonstration projects are under way in rail and ferries.

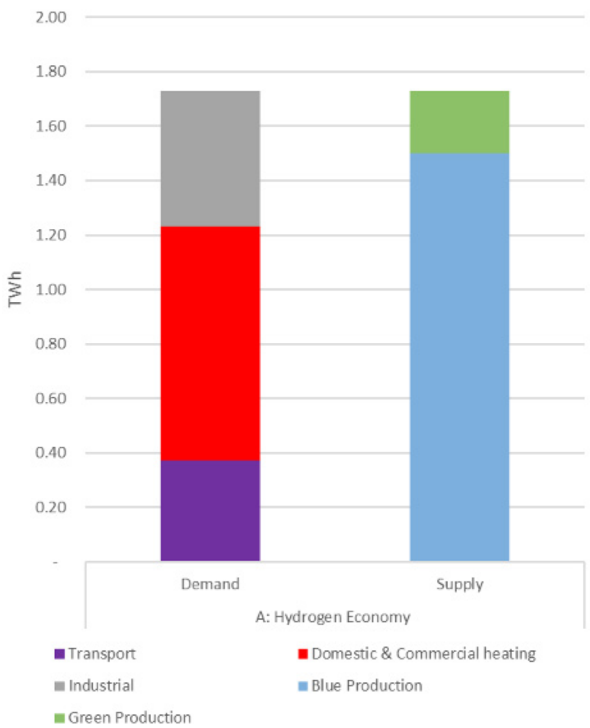


**Figure 3:** Scenario A: Hydrogen Economy - hydrogen usage in 2025 in TWh.

**[2]** 2% volume is less than 2% of energy due to hydrogens lower density compared to natural gas Note that this scenario envisages blending into the transmission network so that the hydrogen makes its way into the whole UK system, for the purposes of this scenario we imagine that this hydrogen is considered for accounting purposes to be used in Scotland.

The remainder of the hydrogen is from small scale electrolyser co-located with demand points spread throughout Scotland. Most of this production is used in transport, though there is some use in heating in pilot projects such as the H100 project in Fife. There is some initial usage of green hydrogen in industry that is not already connected to the gas network.

### *A3.2.1.3 MEDIUM TERM – 2032*

A full hydrogen economy is well on its way to being developed by 2032. There is now just over 20 TWh of hydrogen being produced and used in Scotland.

Blue hydrogen production still makes up over two thirds of production, met by an expanded Acorn facility in Aberdeen, as well as small blue facilities centred in industrial clusters, such as Grangemouth. However, green hydrogen production has ramped up. Both Small to medium scale production from onshore renewables and larger scale offshore production facilities have begun to start producing hydrogen particularly along the east coast.

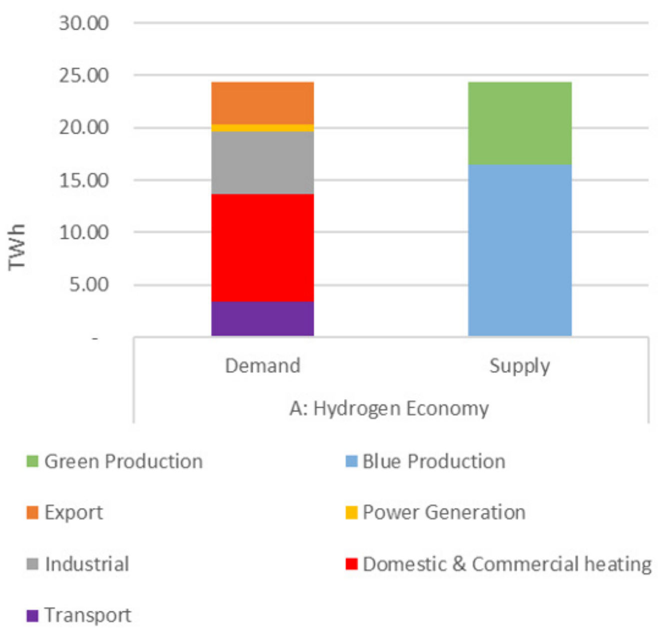


**Figure 4:** Hydrogen Economy development medium term demand and supply (2032).

Conversion of the gas network is the greatest contributor to demand, the blending rate has increased (up to 20% hydrogen blending by volume is thought to be possible without changing domestic and commercial appliances[117]) and in addition whole areas of the grid have been converted to run on 100% hydrogen. These areas are likely to be around the north east, where the Acorn facility has expanded significantly and in the industrial cluster where further blue hydrogen production facilities have been built. Some small amounts of hydrogen are being used in 'peaking plants' that provide back-up for renewable generation. At this stage this may be blended with natural gas rather than 100% hydrogen.

Transport usage has grown, albeit not as much as heating and industrial. It is the larger service vehicles that are driving the demand particularly buses and HGVs Hydrogen is used in a limited number of smaller vehicles, cars and LGVs, but this is largely limited to fleet operated vehicles public sector, and at this stage some limited private sector fleets (delivery vehicles etc). Rail and ferries have moved beyond pilot stage and are now significantly using hydrogen. Hydrogen has begun to be used on a pilot basis, in small domestic aircraft that link small remote airports.

A significant amount of hydrogen produced in Scotland is being used in the rest of the UK as hydrogen is increasingly transmitted via the UK transmission network, still blended with natural gas. Scotland becomes a net exporter of hydrogen to the rest of the UK by 4TWh simply by inputting hydrogen to the gas network.

#### *A3.2.1.4 2045 – NET-ZERO*

Both blue and green production has grown, but green production has accelerated further and has now overtaken blue production. This is particularly driven by hydrogen made at scale using energy from offshore wind farms. Smaller scale production from onshore wind is a smaller, but important part of the production mix particularly in remote and island areas.

A full gas network operates in 2045 as it does today, but with natural gas replaced by hydrogen. Due to its large potential for hydrogen production, Scotland is expected to become a net exporter of hydrogen to the rest of the UK, via the national grid with around 20 TWh. In order to meet fluctuating demands and winter peaks, significant amounts of geological storage requirement is expected. More hydrogen is used in peaking plants

By 2045 hydrogen will be the predominant fuel in residential and commercial heating alongside its use as an industrial feedstock. Hydrogen is now the main fuel for heavy, fleet-based transport e.g. buses, HGVs, trains (non electrified, more remote lines) and water transport and domestic aviation[3]. HGVs become the largest users of hydrogen in the transport sector with all HGVs now using hydrogen. This scenario does not envisage hydrogen becoming the main transport fuel for LGVs and personal vehicles, where EVs are mostly used. There is some usage in this sector primarily in vehicle fleets, such as council vehicles, delivery fleets, company cars etc.,) and in larger personal vehicles. Generally, the larger the vehicle and the longer the distance it needs to travel without stopping, the more likely it is to use hydrogen.

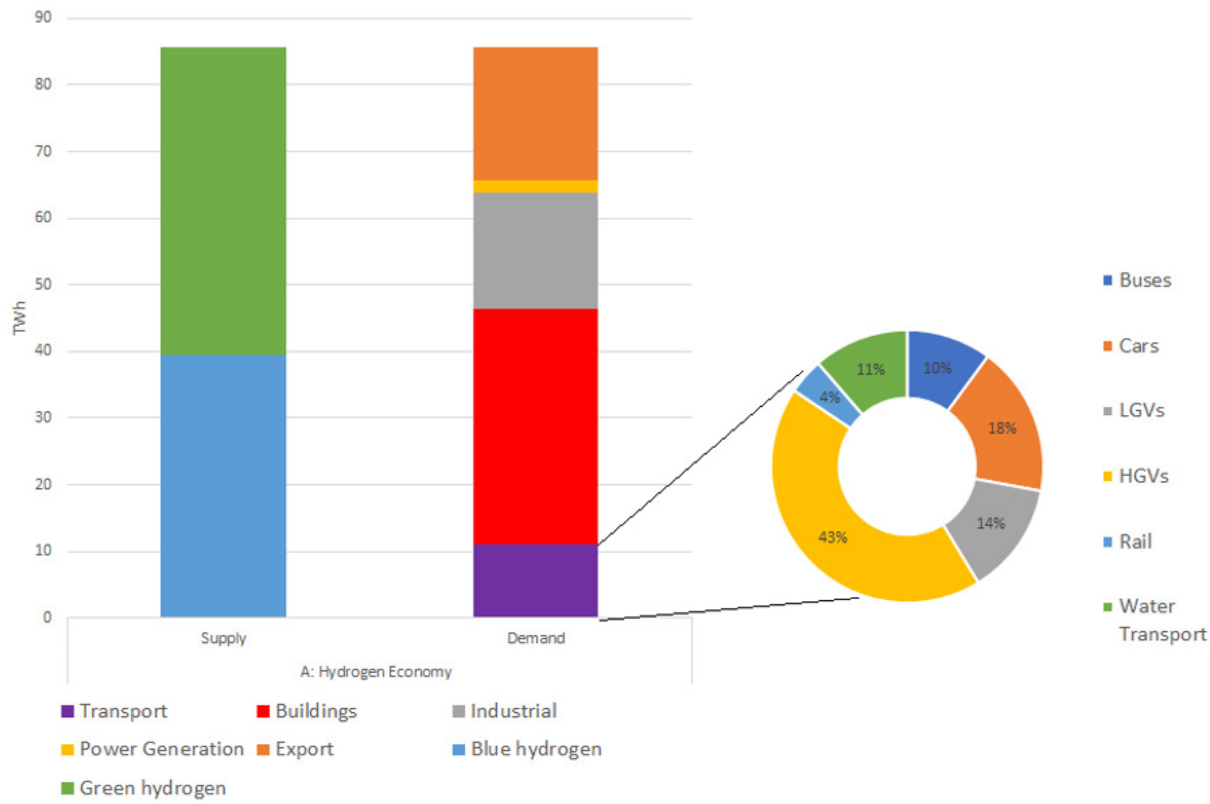


**Figure 5:** Hydrogen Economy supply and demand in 2045 and a breakdown of transport demand use.

**[3]** Note this report has only looked at Scotland's domestic demand so international aviation and shipping are not included in the figures presented.

### A3.2.2 SCENARIO B: GREEN EXPORT

#### A3.2.2.1 THE DEVELOPMENT OF THIS SCENARIO

This scenario is developed from the long listed scenarios where Scotland becomes a mass exporter of hydrogen and where only green hydrogen is produced. The central logic of this scenario is that a large demand for green hydrogen develops in Europe, with Scotland becoming one of the centres of production to meet this need.

This scenario reflects the view from many stakeholders that there is a significant opportunity for hydrogen to utilise Scotland's significant offshore wind resources, that may otherwise not be utilised.

This scenario reflects the views expressed by some stakeholders that only green production should be considered in Scotland. It also reflects the view from some stakeholders that green hydrogen should be seen as a higher value product used where it can most effectively replace fossil fuels. This includes fuel cells (primarily in FCVs), as an industrial feedstock and higher grade heating, rather than as a combustion fuel in the distribution network for domestic and commercial heating.

This scenario explores a world where hydrogen is used extensively in all transport applications not just in fleet and heavy vehicles. Although the indications from literature and stakeholders is that hydrogen is less likely to be used over BEVs in the personal vehicle market there is a view that this could happen so it was felt that it was worth exploring in one scenario. In this scenario there is large amounts of green hydrogen making it more likely that it will be used in hydrogen.

This scenario is overall the most ambitious when it comes to hydrogen production in 2045. Although the build-out rate is slower than in the hydrogen production scenario reflecting that facts that no blue hydrogen is used in this scenario, electrolyser production will take time to ramp-up and an export market will take time to emerge.

#### A3.2.2.2 SHORT TERM - 2025

There is no blue hydrogen in this scenario so overall production is lower than in Hydrogen Economy. However this scenario does show an ambitious roll out of around 400 MW of electrolysers to be deployed in many small scale onshore production facilities throughout the country, located on or close to demand points. These demand points are mostly local fleet transport refuelling stations. Buses lead this demand, together with some public sector, local delivery vehicles and HGVs. A very small number of cars start to be seen on the roads, these are mostly operated in fleets rather than personal vehicles. At this stage the number of vehicles is still limited and based on where hydrogen is available, still far from a national system.

Hydrogen is used at in some industrial processes using hydrogen produced locally from local renewable sources. Hydrogen is not blended into the existing distribution network and is therefore not used in domestic and commercial buildings.

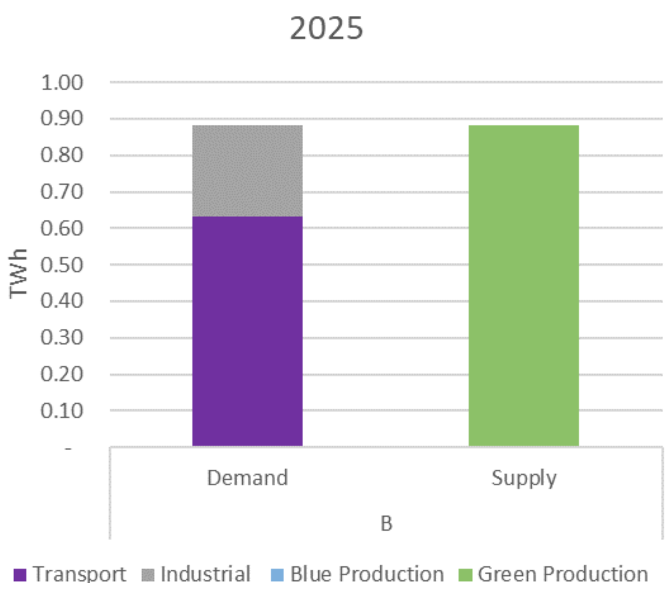


**Figure 6:** Scenario B short term development supply and demand (2025).

### A3.2.2.3 MEDIUM TERM – 2032

By 2032 there will be significant expansion in the size and number of onshore sites, which are co-located with the demand. Additionally, large scale production of hydrogen from dedicated offshore wind sites has come online and is expanding.

By 2032 there is an increase in hydrogen fleet vehicles in this scenario, in addition to uptake in personal hydrogen FCVs. This is expected to coincide, and be driven by, the ban on petrol and diesel vehicles in 2032. Hydrogen vehicles now make up most new vehicle sales, though EVs are also around a third.

Some large scale industrial processes have now been converted to green hydrogen directly connecting to production sources via new pipelines. This includes a small amount of hydrogen being used in peaking plant power generation.

Hydrogen is starting to be exported to the rest of the UK, with a pipeline constructed, or an existing pipeline adapted, connecting with northern England. Much of the offshore production is exported directly by ship to markets in Europe.

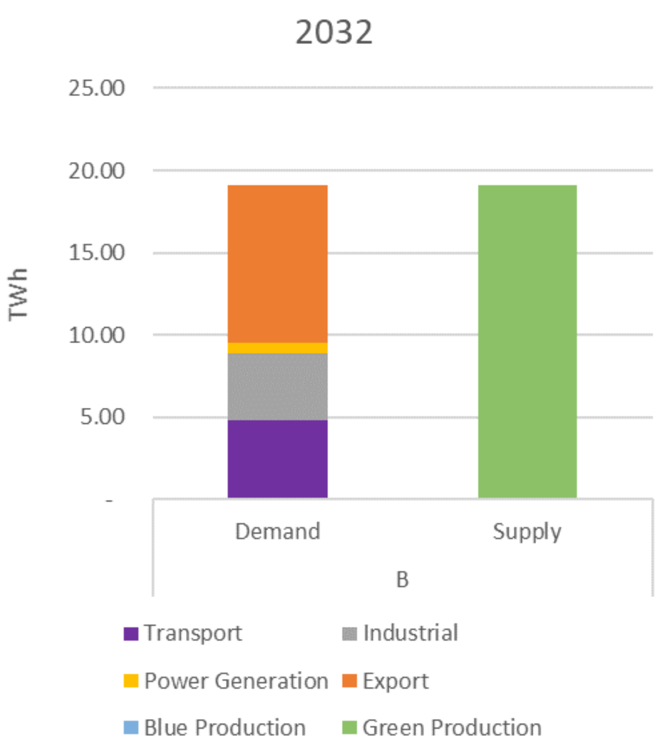


**Figure 7:** Scenario B short term development supply and demand (2025).

### A3.2.2.4 2045 – NET-ZERO

This scenario sees large scale green hydrogen production by 2045, offshore wind is the main contributor to this. Scotland becomes one of Europe's major green hydrogen production centres. The hydrogen is shipped from ports or directly from offshore production platforms to demand centres in continental Europe. Pipelines also connect Scotland to the rest of the UK.

A full hydrogen refuelling network for transport is in place and a proportion of industrial users, both in large industrial clusters and rural and island areas, use hydrogen.

Hydrogen demand points are either directly connected to the new hydrogen pipelines and/or converted natural gas transmission lines, supplied by co-located green production or supplied by road tanker from regional distribution centres.

Storage is required to ensure supply and demand can be balanced, though not as much as other scenarios as demand is not as seasonal, as hydrogen is not used in heating. This also includes some storage to support export from port facilities.

By 2045 nearly all petrol and diesel vehicles have been replaced and hydrogen has become a primary fuel in the transport sector. Although EVs are also a significant part of the mix particularly in the smaller personal vehicle market segment. Usage in cars is the largest proportion of demand in this scenario. Hydrogen is now being used in domestic aviation and shipping[4].

Hydrogen is used within industry both as a feedstock and in industrial heating. Similar to other scenarios hydrogen plays a limited role in power generation helping to supply peak power needs and to balance renewable electricity generation.

**[4]** Demands from international aviation and shipping have not been examined within the scope of this study as they are not considered Scottish demand but here too hydrogen would be expected to paly a key role.

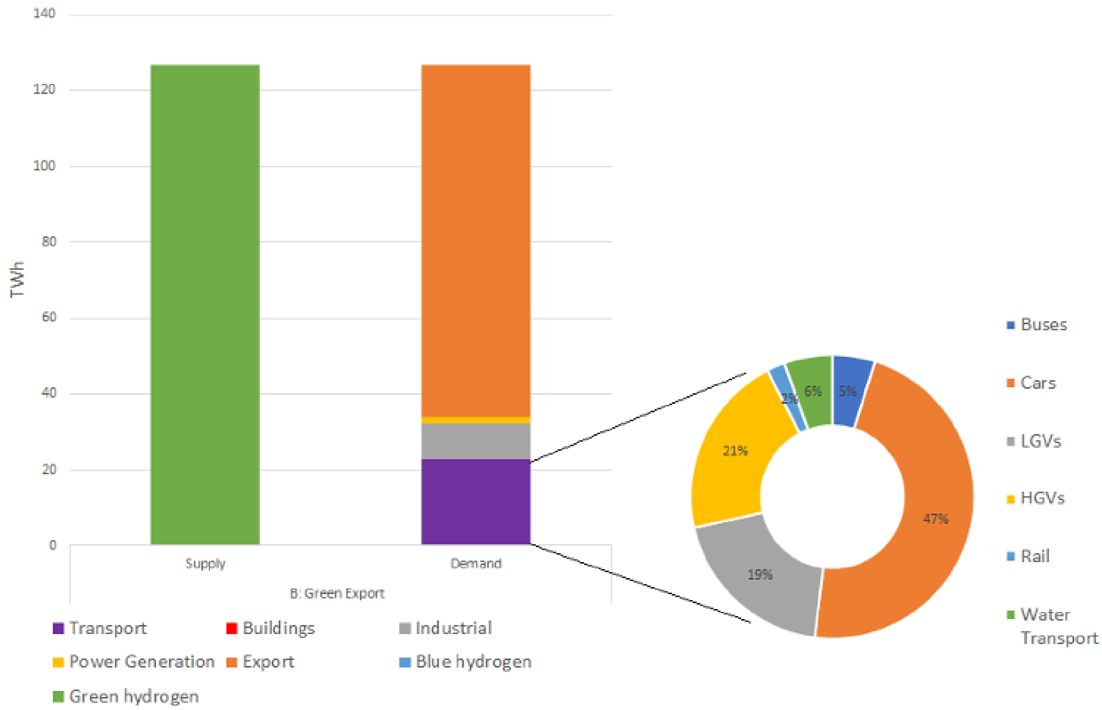


**Figure 8:** Scenario B supply and demand 2045 and a breakdown of transport demand use.

### A3.2.3 SCENARIO C: FOCUSED HYDROGEN

#### A3.2.3.1 THE DEVELOPMENT OF THIS SCENARIO

This scenario is developed from the long listed scenarios where hydrogen is only used for specific regions and particular areas. The central logic of this scenario is that hydrogen is used where it most makes sense to support decarbonisation. The net-zero target is primarily met by electrification with hydrogen playing a supporting role.

This scenario explores the view that hydrogen will only be used in the most low-regret scenarios – in heavy transport fleets and in industry and heating only where hydrogen can be easily produced.

Hydrogen is only used in particular areas of Scotland, with stakeholders identifying the east coast, particularly north east for blue hydrogen production, and rural and island locations with a lot of renewable resources which hydrogen could help to unlock.

#### A3.2.3.2 SHORT TERM – 2045

At the short term stage of this scenario there is no blue hydrogen production as the low-level demand for hydrogen does not warrant a blue hydrogen facility. There is however green production with 150 MW of electrolysers deployed predominantly with onshore wind co-located or near to demand points. These are concentrated in rural and island locations. Many of these sites will use constrained wind resources. Some of these sites will have back-up connection to grid electricity to ensure enough hydrogen can be produced to meet demand.

Transport is the largest proportion of demand, but is still a lower overall number compared to the other scenarios. There will be conversion of a small number of fleet vehicles, primarily buses and some limited use in HGVs, concentrated in certain areas where hydrogen is developing including the north east (Aberdeen hub) and remote and island locations. Hydrogen is not yet in the distribution network at this stage. There is some usage of hydrogen in industrial processes which use hydrogen that is produced locally such as food and drink production in areas not connected to the gas network.

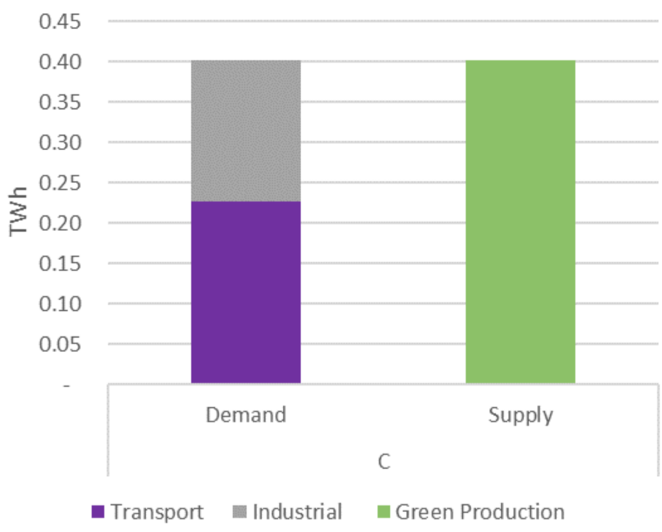


**Figure 9:** Scenario C Focused hydrogen supply and demand in 2025.

#### A3.2.3.3 MEDIUM TERM – 2032

By 2032 a blue hydrogen production facility (Acorn) will come online to supply the local network in the north east. There will also be a modest expansion in the size and scale of onshore renewables, consisting of many small sites co-located with demand points. There is no large scale offshore wind used in this scenario for green hydrogen production.

There will be an increase in fleet vehicle usage in the areas where hydrogen is being produced e.g. east coast, rural and islands locations. Blending of hydrogen will be introduced into the distribution network, including limited conversion of the regional network in the north east and the small local 'off grid' networks in rural areas[5]. In turn there will be an increased blend of hydrogen in existing industrial gas use and some conversion of smaller scale industrial processes particularly in the north east, rural and island locations. As in other scenarios hydrogen is used in a small way in gas fired peaking power plants.

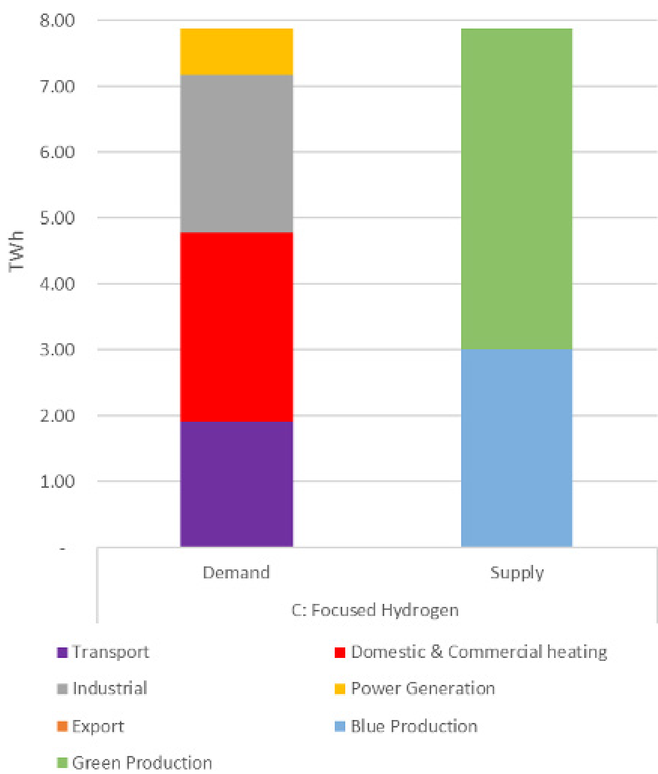


**Figure 10:** Focused hydrogen supply and demand in 2032.

**[5]** Known as Statutory Independent Undertakings (SIUs) these are local gas networks which connected a small number of homes and business but are not connected to the main grid by pipeline, instead being supplied via LNG or LPG tankers.

### *A3.2.3.4 2045 – NET-ZERO*

Hydrogen production has risen by 2045 but by a more modest scale then the other scenarios. Most hydrogen is used near to where it's produced there is very little movement around the country and no export. The blue hydrogen production facility in the north east is expanded to provide the backbone of hydrogen supply in Aberdeen and the hydrogen network is expanded along the east coast.

Green hydrogen production from many onshore wind, and other renewable sources such as wave and tidal, has expanded and is mainly used to directly supply demand points or is fed into small local grids. This green hydrogen is particularly important in rural and island areas allowing for these communities to harness and store the energy to be used in transport, heating and industry. There remains no large scale offshore production.

Hydrogen is used across different sectors in fleet transport, industry and commercial heating, but at a much smaller scale and regionally based. A relatively large demand sector in this scenario is HGVs, where hydrogen has a big advantage over EVs. Hydrogen refuelling centres are spread around the country, though not as many as other scenarios. In areas where there isn't a local hydrogen grid these refuelling centres use a combination of co-located hydrogen production, primarily from onshore wind and grid electricity and some limited tube trailer distribution.

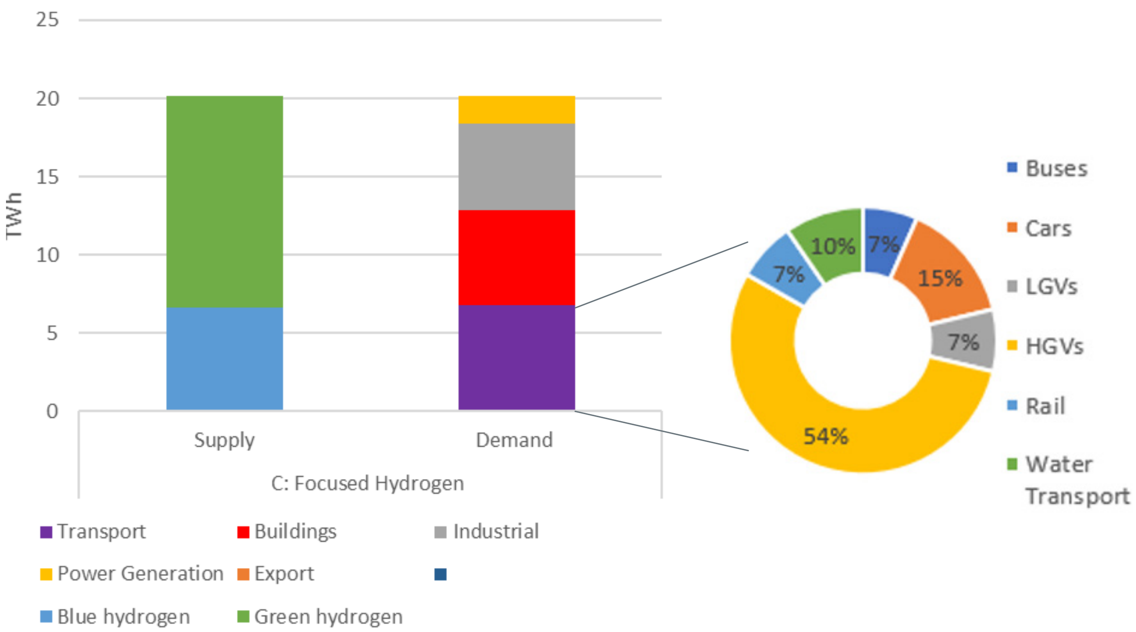


**Figure 11:** Scenario C Focused Hydrogen supply and demand in 2045 and a breakdown of transport demand.

ARUP

SCOTTISH HYDROGEN
ASSESSMENT PROJECT

# APPENDIX 4

## *Economic Assessment*

Scottish Government
Riaghaltas na h-Alba
gov.scot

Scottish Enterprise

HIE

## A4.1 OVERVIEW AND PURPOSE

### A4.1.1 AIMS OF THE IMPACT ASSESSMENT

The impact assessment is aimed at developing a quantitative picture of the socio-economic benefits that could arise from each of the defined scenarios and provide insights into the opportunities they might provide in terms of wealth and job-creation. While the global and European market for hydrogen technologies is still small, it is growing rapidly and expected to continue to do so, presenting an opportunity for Scotland in critical areas. This study seeks to evaluate and quantify the size of that opportunity.

As set out in this report, hydrogen could bring significant benefits across the energy and transport systems, enabling low carbon, zero air quality emissions options, and efficient energy conversion. Whilst these benefits may be achieved irrespective of the geographical origin of the technologies used, the benefits to Scotland could be greater if the supply chain in Scotland for fuel cells and hydrogen were to play a strong role. These benefits could be:

- Economic: as an expanding area for green growth, generating revenue for Scotland and potentially creating highly skilled jobs in a knowledge-based sector;
- Environmental: through ensuring that the technologies developed are appropriate for the Scottish market, are available for Scottish deployment when required, and because there may be greater willingness to promote and support deployment of Scottish technologies in Scotland.

The Scottish hydrogen sector is quite diverse and Scotland has already undertaken studies to map its own fuel cell and hydrogen industry and knowledge-based actors[120]. Many European countries have done the same including the UK as a whole, e.g. Fuel Cell Industry Guide Germany 2016[121], Hydrogen and Fuel Cells: Opportunities for Growth – A Roadmap for the UK[122], Swiss Hydrogen & Fuel Cell Activities: Opportunities, barriers and public support[123].

In contrast to the work referenced above, this study systematically looks at selected value chains to assess the economic impact on Scotland and in that sense builds on the GVA analysis previously conducted on behalf of Scottish Enterprise. The study provides both quantitative outputs and qualitative commentary on the possible economic value created within those sectors assumed to convert wholly or partially to the use of hydrogen under the three scenarios and in each analysis year.

### A4.1.2 OUTPUTS FROM THE STUDY

For each scenario defined in Section 6 (and A3 of this appendix) and in each timeframe (i.e. 2025, 2032 and 2045), we provide a measure of the economic value and of the number of jobs created which is built up from the economic value-added calculated for each specific value chain. GVA and jobs are identified according to the sector under which they fall as defined within the UK Blue Book124. In the commentary we provide additional colour relating to the types of employment and the possible location for both these and the value added depending on where activities take place. In certain instances, these will be clustered around particular areas of expertise, e.g. bus assembly in Falkirk, or where natural resources dictate the siting of plant, e.g. green hydrogen production.

### A4.1.3 LIMITATIONS OF THE ANALYSIS

As discussed, this study focuses exclusively on economic activities which are expected to convert in part or in whole to the use of hydrogen as the primary energy carrier. In that sense it is neither a whole energy system model nor a full or partial economic equilibrium model. This is important since it raises issues around the question of additionality. We attribute value to the sectors under consideration without reference to how the needs of the economy would be satisfied in the absence of hydrogen as an energy source or carrier. If hydrogen is not used to power low-carbon heavy goods vehicles, for example, then another source or carrier would surely be employed whether that be biofuels, electricity directly or some other source not yet considered. Moreover, the needs of the road transport sector are already met using diesel trucks and the value associated with that is already captured in the economy.

This study is not designed to consider the counterfactual case nor does it attempt to distinguish between activities already undertaken and those which may be considered as entirely new. Furthermore, it does not consider the value that may be lost in a move away from fossil fuels and towards hydrogen such as oil refining which would no longer be required after a wholesale move away from carbonaceous fuels.

As such, in heavy duty transport for example, we include all the elements of value involved in the supply, operation and maintenance of heavy duty hydrogen trucks, recognising that some, perhaps most, of this value is already captured in the economy today or might be captured in a different way were an alternative technology to dominate. The question of additionality is addressed in the report through a qualitative exploration of the areas which could be considered as new or replacement.

## A4.2 APPROACH TAKEN

### *A4.2.1 OVERALL LOGIC*

Our approach to the impact assessment involves two stages: firstly to estimate the total gross value added associated with the hydrogen-related activities in each scenario and secondly to identify how much of that value that could be captured in Scotland. This is illustrated below in Figure 12.

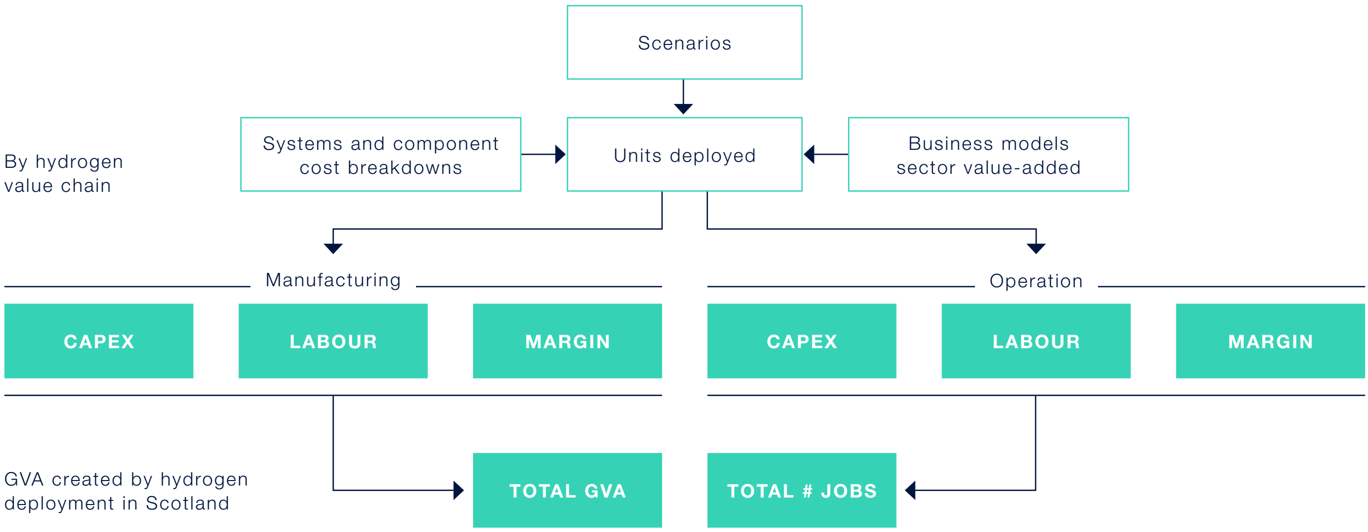


**Figure 12:** Overall approach to GVA.

**Estimation of total gross value-added:** GVA is estimated for each of the hydrogen activities that the scenarios deploy using a bottom-up approach. For the hydrogen technologies, we use detailed technology cost projections that include the contributions of materials, labour, capital equipment (capex) and margin. As discussed, labour, capex and margin all contribute to direct creation of GVA for the manufacturer being considered. The material cost contribution drives the creation of indirect GVA by generating economic activity upstream in the manufacturer's supply chain. Since the supply chain for hydrogen technologies is still largely emerging, opportunities exist to capture positions in both system manufacturing as well as in the supply chain if relevant skills exist or if the market is large enough to justify local manufacturing. We therefore consider the GVA created in the manufacture of the systems as well as the key hydrogen-related subsystems and components that go into those systems, if appropriate. Operation of the deployed hydrogen technologies can also generate GVA in the form of labour and margin and for some applications, such as the export of hydrogen, this is particularly significant. This GVA is also estimated, using established business models and economic multipliers for similar economic activities. For some applications the future business model is either uncertain or expected to be quite complex. For instance, electrolysers may be operated to generate hydrogen for a range of applications, provide ancillary services to the electricity grid, and/or provide energy storage or any combination of those functions. In those instances, the GVA estimates are rather indicative.

**Estimation of gross value-added in Scotland:** Over the time period being considered in the study, the hydrogen sector is expected to be industrializing with new manufacturing capacity being built and new actors joining the supply chain. This evolution will create opportunities for regions including Scotland to capture some of the socio-economic benefits that this growing sector will generate. Whether and to what extent the GVA from deploying and operating hydrogen technologies in Scotland will flow to Scotland, depends on Scotland's position in the relevant value chain.

Circumstances in which at least some of the GVA would flow to Scotland would include:

- operation of the systems taking place in Scotland;
- manufacturing of the systems taking place in Scotland;
- manufacturing of components or capital equipment used in downstream manufacturing of hydrogen technologies taking place in Scotland;
- manufacturing of systems or components being undertaken by Scottish business entities, regardless of location:
- and sales of hydrogen for export

The information gathered in the baselining exercise is used to assess what fraction of the overall GVA could reasonably expect to be captured in Scotland. Data gathering and stakeholder engagement were used to extend the existing database of fuel-cell and hydrogen actors to ensure that it includes the most up to date information on relevant Scottish actors. A qualitative assessment of the relative strength of the relevant Scottish actors was then used to attribute a fraction of the appropriate GVA streams to Scotland for each technology prescribed by the scenarios. The bottom-up GVA assessment approach allowed this assessment to be conducted in a granular fashion, potentially looking at the strengths of specific system or component manufacturers where relevant.

### A4.2.2 DEFINING VALUE ADDED

The assessment of the value creation potential of activities within the hydrogen sector uses an economic value-added approach, where gross value-added equates to the sum of compensation of labour, return on capital, i.e. annualised capital expenditures and margin, i.e. gross profits, as shown in Figure 13.

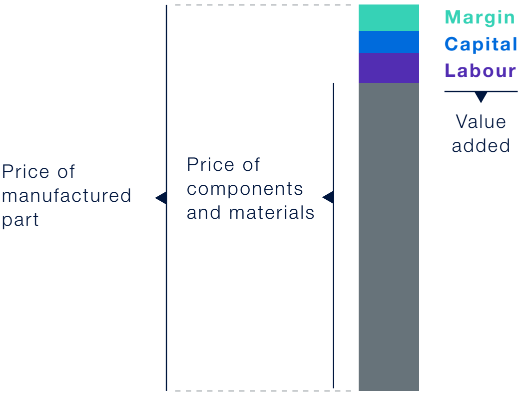


**Figure 13:** Definition of value added.

In practice, for manufactured products, value-added is the difference between the price of a manufactured part and the price of the materials and components used to manufacture it. It is typically a small fraction of the overall price of the part. Equivalently, value-added is the difference between the value of production outputs, i.e. sales revenue or turnover, and the cost of intermediate production inputs, including overhead costs.

For many activities in the hydrogen sector Scotland will likely be involved in the sale, installation, operation and maintenance of equipment produced elsewhere. This could include equipment to produce hydrogen or applications which use hydrogen as an energy source or carrier. In these instances, value-added will relate primarily to the utilisation of assets, e.g. fuel cell buses or steam methane reforming plants, and the employment of labour to install and operate equipment, e.g. hydrogen refuelling stations.

Value is added at each stage of the supply chain and in later stages, value-added from earlier stages becomes part of the price of material, see Figure 14. By tracking the value-added for key components as well as for the system, the study is able to provide insight into which parts of the supply chain have the potential to create the biggest economic benefits.

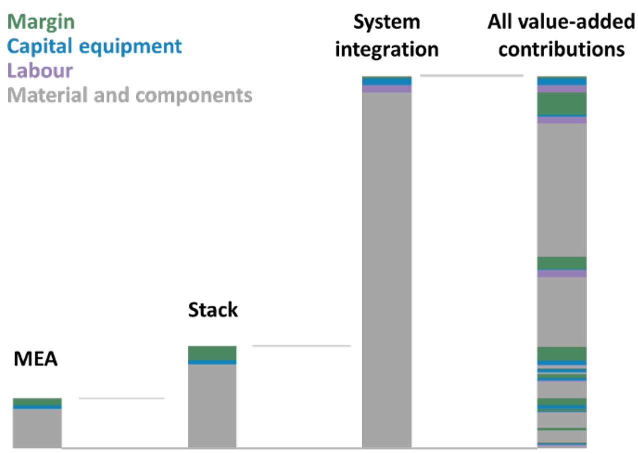


**Figure 14:** Build-up of value-added through the supply chain illustrating that value-added is typically a small fraction of turnover.

As discussed, the estimation of gross value-added potential is composed of three components: labour, capital and margin and they yield benefits in different ways:

***Labour***

- Value is captured as local employment
- Manufacturing plants located in Scotland yield Scottish value
- Home country of business entity is not critical

***Capital***

- Value is captured by suppliers of capital equipment
- Requires Scottish capital equipment suppliers to yield Scottish value

***Margin***

- Captured as revenues of business entity
- Requires Scottish business entity to yield Scottish value

The estimates provided are indicative only. Their purpose is to support the assessment of the relative value creation potential across selected hydrogen value chains at the system level, and from the production and operation of different components and sub-systems, including assembly, integration and maintenance activities. The estimates are based on assumed 'typical' operational structures and cost estimates, and assumptions on cost development occurring over time and for different production scales. The estimates are used to categorise the value creation potential of production activities within the supply chain and should not be interpreted as estimates of actual future value-added potential. Note that all monetary values are expressed in current (2020) prices.

### A4.2.3 MODEL DESIGN

The model is generally bottom-up in design although as we will discuss a partially top down approach has been taken for certain economic activities, see Figure 15.

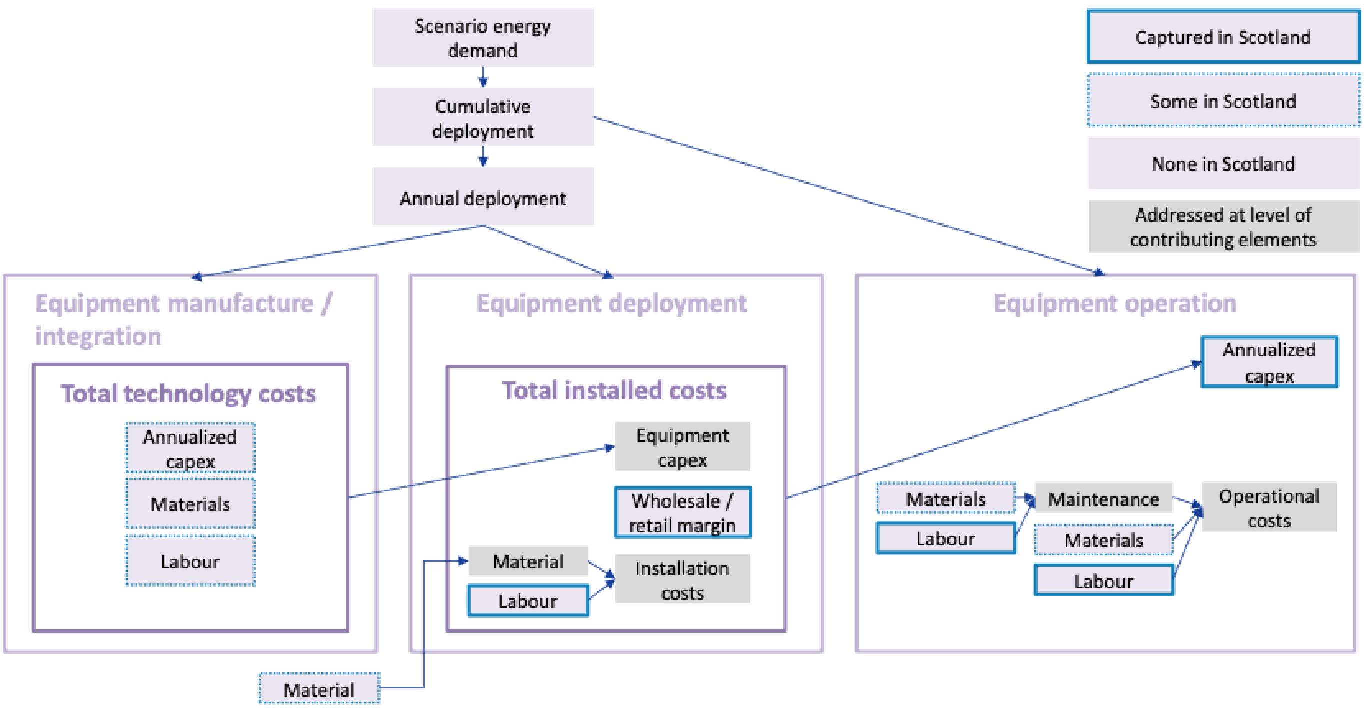


**Figure 15:** Conceptual design.

The conceptual design aspects are set out in the following paragraphs.

**Identification of relevant economic activities:**
The scenario definitions were used to identify all the economic activities that would need to be modelled across all three scenarios, although not all the economic activities are relevant to all scenarios. For example, the **Green Export** scenario does not consider the use of hydrogen for heat while in Scenarios A **Hydrogen Economy** and C **Focused Hydrogen** this is envisaged to a greater or lesser degree; by contrast, green hydrogen production would be a common economic activity across three scenarios. An economic activity is defined as any identifiable activity which can be discreetly defined from a value perspective and will usually relate to a company or set of companies in a given sector. For example, bus operation is considered to be one economic activity, while bus assembly is considered to be a separate economic activity even though these are related to one another.

Identification of the sources of value within economic activity: Estimation of the value attributable to each economic activity requires it to be broken down into its component activities in order that the sources of margin, labour, utilisation and margin can be identified. By way of illustration, taking the case of bus operation, the following sources of value can be identified:

- Bus: A capital asset the value of which relates to the annual capital recovery factor, roughly equivalent to the real depreciation of the asset;
- Bus operation: Cost of labour required to operate the bus and of the organisation required to support operation which includes both indirect labour and other costs such as buildings, ticket printing etc.;
- Fuelling: Cost of fuel required to carry out the day to day journeys undertaken by the bus;
- Bus maintenance: Value of labour required to maintain the bus and of the organisation required to support operation as well as the cost of replacement parts, e.g. replacement of the fuel cell stack;
- And Margin: Profit margin for the bus operator.

As stated above, economic activities can be related, with common inputs and, in certain cases, series relationships. For example, the price of hydrogen is calculated and forms part of the GVA analysis of green and blue hydrogen production economic activities, but this also underpins the calculation of GVA in the bus operation economic activity since fuel use is an input to value creation. Care must be taken to ensure there is no double counting of these elements of value.

Estimation of the per unit value of attributable to economic activity elements: We initially estimate the per unit value associated with each value source and allocate this to one or more of the three areas of added value: capital, labour or margin. For example, for bus operation the unit would be the bus and all values would be calculated on a per bus basis. Broadly speaking, data required can fall into 3 categories:

1. Fixed: The data are based on current values and does not vary over the timeframe of the study; for example, we would assume that a hydrogen bus would be required to cover the same number of miles per day as an equivalent diesel bus today and that this would not change over time or with the number of buses deployed.
2. Time varying: The data vary over the timeframe of the study but not as a direct function of the level of deployment; for example, the number of buses deployed may increase over time as they gradually displace diesel buses.
3. Volume varying: The data vary as a function of the level of deployment; for example, the cost of producing buses may be expected to fall as the cumulative number of buses produced increases either through learning or through scale economies. Needless to say, there is likely to be a time element to this as well but it is deployment not time which is the pertinent feature.

We build on the work recently completed for the Fuel Cells and Hydrogen Joint Undertaking (FCHJU)[120] to define the value-added associated with hydrogen and fuel cell technologies and combine this with data already gathered previously for the Scottish GVA study referenced above. The analysis also draws on E4tech's existing proprietary data and combines it with standard input-output parameters as appropriate to build a picture of each scenario, taking into account levels of confidence and qualitative factors. For certain manufactured components, we employ the learning rate curves, see example in Figure 16, developed in the FCH-JU study, although these are only relevant in a few instances.

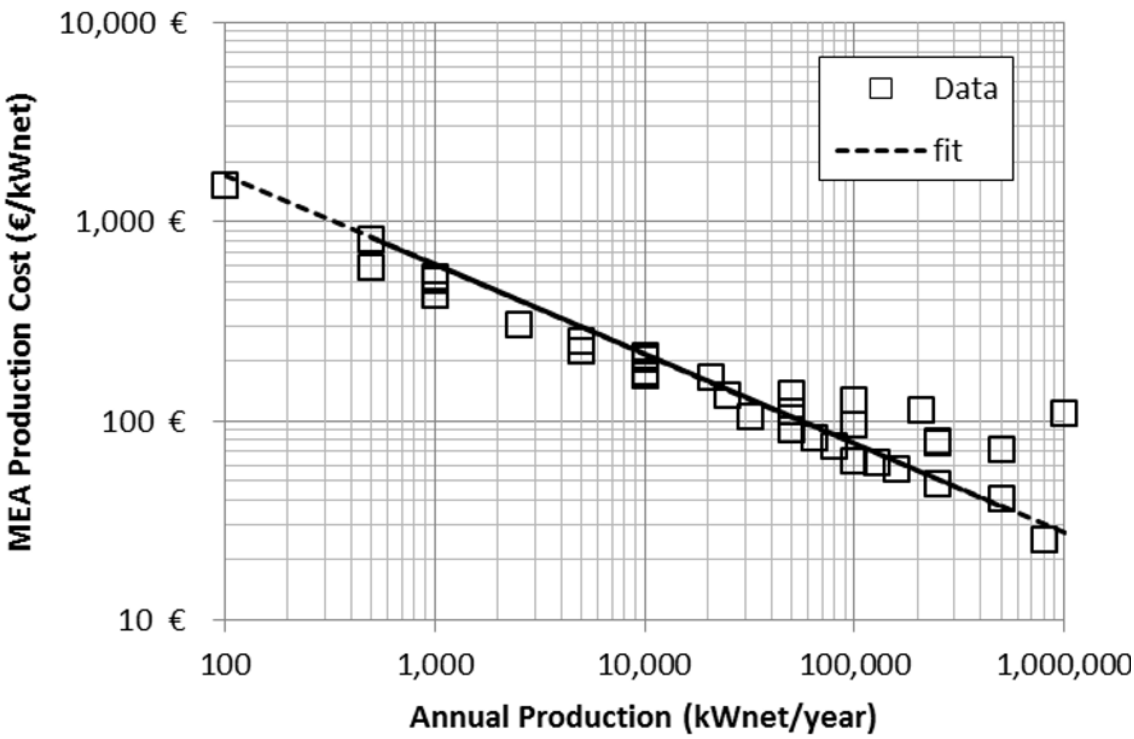


**Figure 16:** Illustrative example of fitting cost analysis data from multiple sources.

Material, labour, and capex splits for each component were derived from the cost studies based on their contributions at full production plant utilization to prevent spurious high capex contributions due to oversized manufacturing equipment.

The distinction between cost and price depends on the perspective within the economic activity. Cost, throughout this analysis refers to a supplier's cost, whereas price refers to the estimated 'factory-gate' price (or cost) for the end-user.

**Estimation of the per unit value of attributable to economic activity elements:** Data from the scenarios is then used to estimate the overall value and jobs created for that particular economic activity under the 3 scenarios and in each timeframe. The data required for each economic activity varies but in the example of bus operation, the principal input required from the scenarios is the number of buses deployed. For each economic activity, the elements of value are identified

**Labour:** salaries are taken from ONS data based on SIC codes for activities and the level of role being considered;

**Capital:** this is taken directly from the calculation of cost estimates and, where necessary, from external sources;

**Margin (or profit):** The estimation of the margin is based on two elements:

- **Standard ('normal') margin.** The standard margin (profit rate) is set at 5% of the total cost of production inputs (labour + capex + materials and other intermediate production inputs), excluding overhead costs. The standard profit rate is applied to all production steps, i.e. production of components and sub-systems, and integration and assembly activities.
- **Excess ('supra-normal') margin.** The excess margin (profit rate) is based on an evaluation of the supply characteristics of each production step. It is intended to 'proxy' the additional margin that may arise as a result of some form of market dominance of firms active within the production step resulting from market (supply) entry barriers. Such barriers may include inter alia intellectual property, e.g. patents, proprietary technology, know-how, etc., investment costs e.g. costs of R&D or production capital, presence of scale economies for incumbent suppliers, etc.

It should be noted that if a standard margin is assumed for all production inputs within a system, and corresponding integration and assembly activities, the estimated market revenues correspond directly with the baseline revenue estimates for the global and EU market deployment scenarios. Where an excess margin is applied to one or more elements of the supply chain, it results in higher revenue estimates than those of the baseline market deployment scenarios.

## A4.3 MODEL IMPLEMENTATION

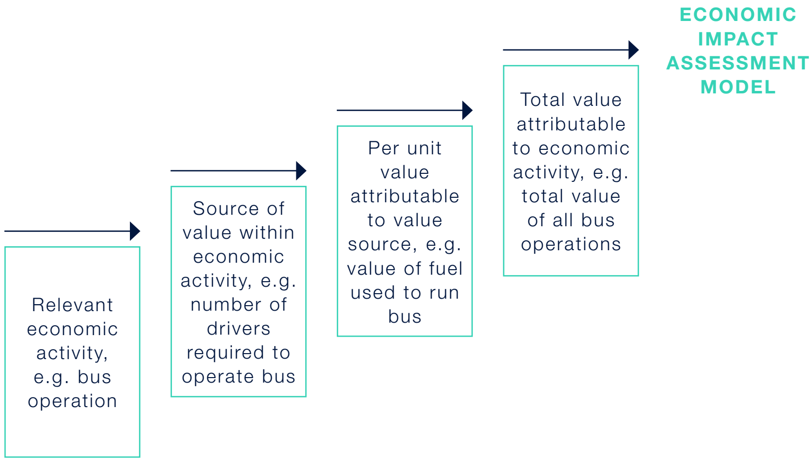


**Figure 17:** Key conceptual design aspects.

The GVA model is implemented in Excel following the logic shown in Figure 17 and consists of a series of calculation sheets, one for each of the economic activities, a summary output sheet which presents the overall GVA and jobs results and a number of input sheets.

**Economic activity sheets**: Each economic activity sheet follows a similar format. Parameters required to calculate the sources of value are laid out in rows while columns present input values or calculated values associated with these parameters. The initial group of columns present starting values while the sets of columns further to the right present the values for each of the scenarios and each of the timeframes for analysis. As discussed, estimates of the value-added that could potentially be generated by operating the fuel cell and hydrogen technologies was based on previous analyses or public sources. Where necessary, suitable economic multipliers were used to fill data gaps or complement the bottom-up data. For more generic items within the supply chain or where established historical data already exists, e.g. for vehicle manufacture, the chassis or coachwork would not be specific to fuel cell vehicles, standard input-output tables and multipliers could be used.

Parameters are grouped in sets of rows relating to different sources of value and are allocated according to the three contributors, labour, capital and margin. Where necessary, parameters are pulled in from the scenario and other input sheets to allow overall GVA and jobs to be calculated for that specific economic activity.

In most cases a fully bottom up approach to calculating GVA is implemented. This means that the contributions to value are calculated based on figures relating to each element of value. For example, the cost of the bus asset is calculated based on the cost of the bus, according to the cost curves developed in the FCH-JU study and the assumed cumulative number of units built in a given timeframe, an assumed lifetime, based on standard figures for today's diesel buses, and an assumed discount rate which together are used to calculate the annualised capital cost of the bus.

Similarly, the annual direct labour cost of operating the bus is built up from an assumed number of operators required per bus, based on practice today, and an assumed salary derived from ONS data. Indirect costs are based on a standard recovery factor on direct labour which is split between indirect labour and other non-labour cost based on empirical data for typical bus operator businesses.

By contrast, in a number of situations, notably where existing assets are repurposed for use with hydrogen, a more top-down approach has been taken. For example, the value of operating the gas distribution network to transport hydrogen is assumed to be equivalent to the value of operating the same grid to transport natural gas today. Consequently, we have taken the value-added to be equal to the retail price less the wholesale price of natural gas and then allocated that value-added amongst the relevant categories of value. Note that the assets are assumed at this point to be fully amortised and we therefore ignore the capital element beyond any capital recovery that is reflected in the current pricing.

The economic activity sheets are enumerated in Table 9, grouped according to a series of archetypes to facilitate the interpretation of the analysis.

| PRODUCTION | TRANSMISSION AND DISTRIBUTION | TRANSPORT | DOMESTIC, COMMERCIAL AND INDUSTRIAL |
|---|---|---|---|
| Deployment<br>• Offshore green<br>• Onshore green<br>• Blue | Grid operation<br>• Transmission<br>• Distribution | Sales and maintenance<br>• Car dealerships and maintenance | Operation & maintenance<br>• Domestic & Commercial<br>• Industrial<br>• Power generation |
| Operation<br>• Offshore green<br>• Onshore green<br>• Blue | Fuel delivery operation<br>• Truck network | Operation<br>• Buses<br>• HGV<br>• Trains<br>• Ferries | |
| Manufacture<br>• Electrolyser | HRS operation<br>• Private<br>• Public | Manufacture<br>• Buses | |

**Table 9:** List of economic activities grouped by sector and archetype.

### A4.3.1 OUTPUTS

As discussed, for each scenario and in each timeframe (i.e. 2025, 2032 and 2045), we provide a measure of the economic value and of the number of jobs created which is built up from the economic value-added calculated for each specific economic activity. The screenshot in Figure 38 provides an illustration of how the output sheet of the model is organised. As can be seen, GVA and jobs are identified according to the sector under which they fall as defined within the UK Blue Book[6].

**[6]** See https://www.ons.gov.uk/releases/uknationalaccountsthebluebook2019 and associated publications and data tables.

| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Scenario A: Full hydrogen | | | | Scenario B: Green hydrogen | | | | Scenario C: Focused hydrogen | | |
| | | | | | | 2025 | 2032 | 2045 | | 2025 | 2032 | 2045 | | 2025 | 2032 | 2045 |
| **Value added and jobs summary** | | | | | | | | | | | | | | | | |
| Total value added | MGBP | | | | | | | | | | | | | | | |
| Total jobs | unit | | | | | | | | | | | | | | | |
| **Value added breakdown** | | | | | | | | | | | | | | | | |
| Manufacturing | MGBP | | | | | | | | | | | | | | | |
| Gas supply | MGBP | | | | | | | | | | | | | | | |
| Construction / Installation | MGBP | | | | | | | | | | | | | | | |
| Wholesale / Retail / Repair | MGBP | | | | | | | | | | | | | | | |
| Transportation | MGBP | | | | | | | | | | | | | | | |
| Services | MGBP | | | | | | | | | | | | | | | |
| **Jobs breakdown** | | | | | | | | | | | | | | | | |
| Manufacture | unit | | | | | | | | | | | | | | | |
| Retail/wholesale | unit | | | | | | | | | | | | | | | |
| Operation | unit | | | | | | | | | | | | | | | |
| Maintenance | unit | | | | | | | | | | | | | | | |
| Admin | unit | | | | | | | | | | | | | | | |
| **Offshore green H2 deployment** | | | | | | | | | | | | | | | | |
| **Onshore green H2 deployment** | | | | | | | | | | | | | | | | |
| **Blue H2 deployment** | | | | | | | | | | | | | | | | |
| **Offshore green H2 production** | | | | | | | | | | | | | | | | |
| **Onshore green H2 production** | | | | | | | | | | | | | | | | |
| **Blue H2 production** | | | | | | | | | | | | | | | | |

**Figure 18:** Screenshot of output sheet.

Examination of the GVA calculations on the individual sheets allows conclusions to be drawn about type of employment created while the scenarios themselves provide indicators of where activities might be expected to take place. Together these elements contribute to building a qualitative narrative regarding the location of job creation and of value added. It should be noted that this is purely indicative and based on knowledge of where current activities are located, e.g. the location of the ADL bus assembly plant, and educated assumptions with regard to where future activities would be located, e.g. provisioning of offshore hydrogen production is likely to be centred on East Coast ports.

### A4.3.2 APPROACH TO SENSITIVITY ANALYSIS

The three scenarios are designed to represent three possible future end states and as such allow the effect of different assumptions on the resulting GVA and job creation to be explored. They are not intended to be accurate depictions of what happens but possibilities based on a range of current views and assumptions. Accordingly an extensive analysis of the sensitivity of the outputs to changes in individual parameters, e.g. the cost or the deployment numbers of particular assets, within scenarios, has not been carried out.

## A4.4 FIGURE REFERENCE TABLES

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

| | SCENARIO A: HYDROGEN ECONOMY | | | SCENARIO B: GREEN EXPORT | | | SCENARIO C: FOCUSED HYDROGEN | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2025 | 2032 | 2045 | 2025 | 2032 | 2045 | 2025 | 2032 | 2045 |
| Scottish GVA | 0.6 | 5.3 | 16.2 | 0.7 | 6.1 | 25.9 | 0.3 | 2.5 | 5.7 |

**Figure 41**
Total number of Scottish jobs in each scenario

| | SCENARIO A: HYDROGEN ECONOMY | | | SCENARIO B: GREEN EXPORT | | | SCENARIO C: FOCUSED HYDROGEN | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2025 | 2032 | 2045 | 2025 | 2032 | 2045 | 2025 | 2032 | 2045 |
| Scottish jobs | 7,669 | 64,391 | 177,229 | 10,029 | 81,324 | 312,600 | 3,883 | 31,366 | 68,467 |

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

| | SCENARIO A: HYDROGEN ECONOMY | | | SCENARIO B: GREEN EXPORT | | | SCENARIO C: FOCUSED HYDROGEN | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2025 | 2032 | 2045 | 2025 | 2032 | 2045 | 2025 | 2032 | 2045 |
| Production | 0.2 | 2.8 | 9.2 | 0.2 | 3.4 | 19.1 | 0.1 | 1.0 | 1.7 |
| T&D | 0.1 | 0.5 | 1.4 | 0.1 | 0.3 | 0.7 | 0.0 | 0.2 | 0.5 |
| Transport | 0.3 | 1.8 | 5.1 | 0.5 | 2.3 | 6.0 | 0.2 | 1.2 | 3.3 |
| Domestic & Commercial Heat | 0.0 | 0.1 | 0.2 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Industrial | 0.0 | 0.1 | 0.2 | 0.0 | 0.0 | 0.1 | 0.0 | 0.0 | 0.0 |
| Power generation | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

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

| | SCENARIO A: HYDROGEN ECONOMY | | | SCENARIO B: GREEN EXPORT | | | SCENARIO C: FOCUSED HYDROGEN | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2025 | 2032 | 2045 | 2025 | 2032 | 2045 | 2025 | 2032 | 2045 |
| Production | 2,974 | 34,510 | 95,478 | 2,518 | 45,435 | 218,198 | 1,149 | 13,560 | 20,977 |
| T&D | 868 | 4,075 | 9,967 | 939 | 4,449 | 11,190 | 309 | 2,009 | 3,969 |
| Transport | 3,601 | 23,476 | 66,342 | 6,537 | 30,967 | 82,436 | 2,401 | 15,048 | 42,313 |
| Domestic & Commercial Heat | 154 | 1,630 | 3,968 | 0 | 0 | 0 | 0 | 467 | 763 |
| Industrial | 72 | 700 | 1,474 | 35 | 473 | 776 | 25 | 282 | 445 |
| Power generation | 0 | 33 | 81 | 0 | 33 | 81 | 0 | 33 | 81 |

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

| | SCENARIO A: HYDROGEN ECONOMY | | | SCENARIO B: GREEN EXPORT | | | SCENARIO C: FOCUSED HYDROGEN | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2025 | 2032 | 2045 | 2025 | 2032 | 2045 | 2025 | 2032 | 2045 |
| Domestic & Commercial Heat | 154 | 1,630 | 3,968 | 0 | 0 | 0 | 0 | 467 | 763 |

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

| | SCENARIO A: HYDROGEN ECONOMY | | | SCENARIO B: GREEN EXPORT | | | SCENARIO C: FOCUSED HYDROGEN | | |
|---|---|---|---|---|---|---|---|---|---|
| | **2025** | **2032** | **2045** | **2025** | **2032** | **2045** | **2025** | **2032** | **2045** |
| Construction | 2,224 | 19,422 | 30,551 | 1,042 | 17,425 | 60,898 | 475 | 5,717 | 4,208 |
| Operation | 750 | 15,121 | 65,008 | 1,476 | 28,042 | 157,382 | 673 | 7,876 | 16,851 |

**Figure 46**
GVA (£m) by transport sector

| | SCENARIO A: HYDROGEN ECONOMY | | | SCENARIO B: GREEN EXPORT | | | SCENARIO C: FOCUSED HYDROGEN | | |
|---|---|---|---|---|---|---|---|---|---|
| | **2025** | **2032** | **2045** | **2025** | **2032** | **2045** | **2025** | **2032** | **2045** |
| Buses | 154 | 624 | 1,376 | 305 | 998 | 1,533 | 116 | 393 | 548 |
| HGV | 88 | 879 | 2,916 | 147 | 879 | 2,916 | 59 | 587 | 2,197 |
| Rail | 16 | 130 | 325 | 16 | 163 | 325 | 0 | 98 | 326 |
| Ferries | 17 | 137 | 343 | 17 | 137 | 343 | 7 | 86 | 172 |
| Cars & LGV | 1 | 50 | 175 | 4 | 132 | 855 | 1 | 16 | 82 |

**Figure 47**
Number of jobs by ONS category

| | SCENARIO A: HYDROGEN ECONOMY | | | SCENARIO B: GREEN EXPORT | | | SCENARIO C: FOCUSED HYDROGEN | | |
|---|---|---|---|---|---|---|---|---|---|
| | **2025** | **2032** | **2045** | **2025** | **2032** | **2045** | **2025** | **2032** | **2045** |
| Manufacturing | 14 | 286 | 465 | 25 | 326 | 569 | 10 | 196 | 278 |
| Retail/wholesale | 9 | 307 | 531 | 33 | 820 | 2,997 | 6 | 95 | 277 |
| Operation | 2,307 | 14,124 | 39,435 | 4,168 | 17,940 | 40,851 | 1,541 | 9,240 | 25,199 |
| Maintenance | 435 | 3,621 | 11,589 | 807 | 5,342 | 23,188 | 294 | 2,142 | 7,269 |
| Admin | 836 | 5,138 | 14,322 | 1,504 | 6,539 | 14,831 | 550 | 3,375 | 9,290 |

## A4.5 SUPPLY CHAIN CAPABILITIES

Scotland's existing supply chain strengths are well placed to support a hydrogen supply chain and wider economy. Some examples of these strengths are recorded in the tables below.

***Green Hydrogen Production***

| SKILLS | INFRASTRUCTURE AND EQUIPMENT | SUPPLY CHAIN |
|---|---|---|
| Process engineering | Electrolysers | Electrolyser Original Equipment Manufacturers |
| Safety engineering | Electrical balance of plant | Gas system suppliers |
| Control engineering | Gas system balance of plant | Renewable developers |
| Electrical engineering | Wind turbines | Civil contractors |
| Systems engineering | Solar panels | System integrator |
| Renewables engineering | | System operator/ owner |
| Civil engineering | | Grid services specialists |
| Electrolyser and system maintenance | | Consultants |
| Renewables O&M | | Planning |
| Project development | | |

***Blue Hydrogen Production***

| SKILLS | INFRASTRUCTURE AND EQUIPMENT | SUPPLY CHAIN |
|---|---|---|
| Chemical engineering | SMR/ATR plant | Chemical companies |
| Process engineering | Gas terminal | Engineering, procurement, construction contractors |
| Safety engineering | Gas compressor stations | Oil and gas operators |
| Reservoir engineering | Offshore pipelines | Project developers |
| Pipeline design | Offshore platforms | Drilling contractors |
| Well engineering | Wells | Service companies |
| Plant operations & maintenance | Vessels | SMR/ATR OEMs |
| Project development | Drilling rigs | |
| Civil engineering | | |
| Offshore engineering | | |

### *Hydrogen Storage and Transportation*

| SKILLS | INFRASTRUCTURE AND EQUIPMENT | SUPPLY CHAIN |
|---|---|---|
| Civil engineering | Pressure vessels | Logistics companies |
| Process engineering | Pipelines | Gas distribution and transmission network operators |
| Pipeline design | Geological storage | Shipping companies |
| Supply and demand planning | Tankers | Port operators |
| Chemical engineering | Chemical plants | Chemical companies |
| Resevoir engineering | Ports | Storage companies |
| Shipping and logistics | Vessels | Terminal operations |
| Transport and logitscs | | |
| Geology and Geotechncial Engineering | | |

### *Demand – Transport*

| SKILLS | INFRASTRUCTURE AND EQUIPMENT | SUPPLY CHAIN |
|---|---|---|
| Automotive design | Vehicle OEMs (cars, buses, taxis, HGVs) | Fuel cell manufacturers |
| Rolling stock engineers | Shipyards/ fabricator | Vehicle manufacturers |
| Naval architecture | Train OEMs | Vessel constructors |
| Mechanical engineering | Refuelling infrastructure | Train manufacturers |
| Chemical engineering | Fuel cells | Hydrogen refueller manufacturers |
| Fuel cell design | | Transport and logistics consultants |
| Transport planning | | Fleet operators |
| Logistics planning | | Maintenance contractors |
| Vehicle maintenance and repair | | |
| Safety and Testing | | |

### *Demand – Heat and Power*

| SKILLS | INFRASTRUCTURE AND EQUIPMENT | SUPPLY CHAIN |
|---|---|---|
| Safety Engineering | Hydrogen boilers | Fuel cell manufacturers |
| Heating system design | Hydrogen powered gas turbines | Boiler manufacturers |
| Gas installation | Hydrogen fuel cells | Gas turbine manufactures |
| Process engineering | CHP systems | System integrators |
| Mechanical engineering | Power station balance of plant and control systems | Domestic heating contractors |
| Systems engineering | | Gas network operators |
| Fuel cell design | | |
| Installation and maintenance | | |
| Electrical engineering | | |
| Materials Engineering | | |

ARUP

SCOTTISH HYDROGEN
ASSESSMENT PROJECT

# APPENDIX 5

## *References*

Scottish Government
Riaghaltas na h-Alba
gov.scot

Scottish Enterprise

HIE

## A5 APPENDIX REFERENCES

1. Pale Blue Dot. Acorn Hydrogen: Project Summary. (2019).
2. The Oil & Gas Technology Centre. Phase 1 report - OGTC: Delivery of an offshore hyrogen supply programme via industrial trials. 1–34.
3. Orkney Hydrogen | Surf 'n' Turf. http://www.surfnturf.org.uk/.
4. BEIS. Dolphyn Hydrogen Phase 1 - Final Report. (2019).
5. The Carbon Capture & Storage Association (CCSA). Caledonia Clean Energy Project - Feasibility Report . http://www.ccsassociation.org/news-and-events/reports-and-publications/caledonia-clean-energy-project-feasibility-report/ (2018).
6. Hydrogen 100 | SGN Your gas. Our network. https://sgn.co.uk/about-us/future-of-gas/hydrogen/hydrogen-100.
7. SGN. SGN Energy Futures - Hydrogen Vision. https://www.nweurope.eu/media/7096/sgn.pdf (2019).
8. Aberdeen's pioneering hydrogen bus project arrives at major milestone. https://news.aberdeencity.gov.uk/aberdeens-pioneering-hydrogen-bus-project-arrives-at-major-milestone/.
9. Aberdeen Hydrogen Bus Project chalks up year of success. https://news.aberdeencity.gov.uk/aberdeen-hydrogen-bus-project-chalks-up-year-of-success/.
10. HySeasIII. HySeasIII Website. https://www.hyseas3.eu/ (2020).
11. Press release: HySpirits to investigate hydrogen to decarbonise the distilling process : EMEC: European Marine Energy Centre. http://www.emec.org.uk/press-release-hyspirits-to-investigate-the-feasibility-of-hydrogen-as-a-fuel-to-decarbonise-the-distilling-process/.
12. HyTrEc. HyTrEc Website. http://www.hytrec.eu/ (2020).
13. HyDIME. https://hydime.co.uk/ (2020).
14. SWIFTH2. SWIFTH2 project for hydrogen powered ferries in Scotland. Fuel Cells Bull. 2019, 6 (2019).
15. HyFlyer : EMEC: European Marine Energy Centre. http://www.emec.org.uk/projects/hydrogen-projects/hyflyer/.
16. Logan Energy. Logan Energy have opened Central Belt's first hydrogen refuelling station for vehicles . https://www.loganenergy.com/logan-energy-have-opened-central-belts-first-hydrogen-refuelling-station-for-vehicles/ (2020).
17. ULEMCo. ULEMCo to Deliver Hydrogen Fuelled Gritters for Glasgow. https://ulemco.com/?p=2977 (2020).
18. Robertson. UKs largest hydrogen fuel cell arrives at TECA . https://www.robertson.co.uk/news/uks-largest-hydrogen-fuel-cell-arrives-teca (2020).
19. SGN. Methilltoune Phase 1 Feasibility Design Public Summary Report. (2020).
20. UK Research and Innovation & University of Edinburgh. HyStorPor - Hydrogen Storage in Porous Media. https://gtr.ukri.org/projects?ref=EP%2FS027815%2F1 (2019).
21. BIG HIT Website. https://www.bighit.eu/.

22. The Scotsman. Glasgow hydrogen bus hope in time for postponed COP26 conference . https://www.scotsman.com/news/transport/glasgow-hydrogen-bus-hope-time-postponed-cop26-conference-2546946 (2020).
23. Reflex. ReFLEX Orkney. https://mailchi.mp/34bb1617d6dd/reflexorkney (2019).
24. TNEI Element Energy. Evaluation of Niche Transport Opportunities for Scotland. (2017).
25. Bright Green Hydrogen. Hydrogen Office Project. https://www.brightgreenhydrogen.org.uk/hydrogen-office-project/.
26. Bright Green Hydrogen. Levenmouth Community Energy Project. https://www.brightgreenhydrogen.org.uk/levenmouth-community-energy-project/.
27. E4tech. East Neuk Power-to-Hydrogen judged Cross Vector Project of the Year. https://www.e4tech.com/news/2057-east-neuk-power-to-hydrogen-judged-cross-vector-project-of-the-year.php (2020).
28. MSIP. MSIP | Creating a new future for People, Place & Planet. https://www.msipdundee.com/ (2020).
29. Transport Scotland. New accelerator established to drive hydrogen innovation. https://www.transport.gov.scot/news/new-accelerator-established-to-drive-hydrogen-innovation/ (2020).
30. H2 Aberdeen. Aberdeen Hydrogen Hub. http://www.h2aberdeen.com/ (2019).
31. Energy Vice. Opportunity Cromarty Firth reveals hopes for free port to boost jobs for 50 years - News for the Oil and Gas Sector. https://www.energyvoice.com/oilandgas/north-sea/256666/opportunity-cromarty-firth-reveals-hopes-for-free-port-to-boost-jobs-for-50-years/ (2020).
32. Scottish Government. Energy Statistics Database. https://www2.gov.scot/Topics/Statistics/Browse/Business/Energy/Database (2019).
33. Committee on Climate Change. Net Zero - The UK's contribution to stopping global warming. https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/ (2019).
34. The Royal Society. Options for producing low-carbon hydrogen at scale. (2018).
35. Hydrogen storage | Hydrogen. https://hydrogeneurope.eu/hydrogen-storage.
36. Hy4Heat. Conversion of Industrial Heating Equipment to Hydrogen. (2019).
37. ISO. ISO 14687:2019(en), Hydrogen fuel quality . https://www.iso.org/obp/ui/#iso:std:iso:14687:ed-1:v1:en.
38. Arup. Five Minute Guide To Hydrogen - Arup. https://www.arup.com/perspectives/publications/promotional-materials/section/five-minute-guide-to-hydrogen (2016).
39. Staffell, I. et al. The role of hydrogen and fuel cells in the global energy system. Energy Environ. Sci 12, 463 (2019).
40. IEA. Future of Hydrogen. Seizing today's opportunities. Iea (2019).
41. Cranfield University. Bulk Hydrogen Production by Sorbent Enhanced Steam Reforming (HyPER Project). (2019).
42. Kalamaras, C. M., Efstathiou, A. M., Al-Assaf, Y. & Poullikkas, A. Conference Paper Hydrogen Production Technologies: Current State and Future Developments. Conf. Pap. Energy 2013, (2013).
43. Zero Emissions Platform. Future CCS Technologies European Zero Emission Technology and Innovation Platform (p17). https://ec.europa.eu/clima/policies/ets/reform/index_en.htm (2017).

44. CCS Association. Transport – The Carbon Capture & Storage Association (CCSA). http://www.ccsassociation.org/what-is-ccs/transport/ (2020).
45. Carrington, D. UK cancels pioneering £1bn carbon capture and storage competition | Environment | The Guardian. The Guardian (2015).
46. HM Treasury. Budget 2020 - GOV.UK. https://www.gov.uk/government/publications/budget-2020-documents/budget-2020 (2020).
47. Electrolysis: The Way of the Future | Owlcation. https://owlcation.com/stem/Electrolysis-The-Way-of-the-Future (2017).
48. EDF Energy R&D UK Centre. H2H Feasibility Report. (2019).
49. ITM Power. HGas10MW | Largest Electrolyser System. https://www.itm-power.com/hgas10mw.
50. ITM Power. REFHYNE | ITM Power. https://www.itm-power.com/refhyne (2020).
51. Neptune Energy. PosHYdon Pilot Offshore green hydrogen. https://www.ogauthority.co.uk/media/6220/ogauthoritysharepointcom-ssl-davwwwroot-sites-ecm-tbw3-documents-files-exchange-malcolm-workshop-slides-301019-neptune.pdf (2019).
52. The Royal Society. Ammonia: zero-carbon fertiliser, fuel and energy store. (2020).
53. Northern Gas Networks. Leeds City Gate H21. https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf.
54. Health and Saftery Executive. Iron mains risk reduction. 2020 https://www.hse.gov.uk/gas/supply/mainsreplacement/index.htm.
55. Jacobs ELement Enrtgy. Hydrogen supply chain evidence base. (2018).
56. Compressed Hydrogen Storage - an overview (pdf) | ScienceDirect Topics. https://www.sciencedirect.com/topics/engineering/compressed-hydrogen-storage/pdf.
57. Pale Blue Dot. Hydrogen Supply Chain Mapping Report. (2018).
58. Andersson, J. & Grönkvist, S. Large-scale storage of hydrogen. International Journal of Hydrogen Energy vol. 44 11901–11919 (2019).
59. Beckmann, M., Pieper, C. & Dresden, T. U. Readiness level of technologies for the “Energiewende”: Results from VGB Scientific Advisory Board study. (2019).
60. WHY BRITAIN URGENTLY NEEDS A LOW CARBON HEAT STRATEGY. www.policyconnect.org.uk (2019).
61. Hydrogen Council. Path to hydrogen competitiveness, a cost perspective. (2020).
62. Hydrogen Europe. Hydrogen Applications | Hydrogen. https://hydrogeneurope.eu/hydrogen-applications (2020).
63. Hy4Heat. Hy4Heat Engagement Event 16 March Q&A. https://static1.squarespace.com/static/5b8eae345cfd799896a803f4/t/5bb1ea0d24a6948a7581acc8/1538386446251/16+March+2018+event+Q%26A+.pdf.
64. Fuel Cell Hydrogen (FCH). Fuel Cells and Hydrogen for Green Energy in European Cities and Regions A Study for the Fuel Cells and Hydrogen Joint Undertaking. https://www.fch.europa.eu/sites/default/files/180926_FCHJU_Regions_Cities_Final_Report.pdf (2018).

65. Matthews, P. & Scherr, I. Annual Compendium of Scottish Energy Statistics. https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2019/05/annual-compendium-of-scottish-energy-statistics/documents/annual-compendium-may-2019/annual-compendium-may-2019/govscot:document/Annual%2BCompendium%2Bof%2BScottish%2BEnergy%2BStatistics.pdf (2019).
66. Scottish Government. Scottish Energy Strategy: The future of energy in Scotland. (2017).
67. statistics.gov.scot : Energy Consumption. Scottish Government https://statistics.gov.scot/resource?uri=http%3A%2F%2Fstatistics.gov.scot%2Fdata%2Fenergy-consumption (2020).
68. Cadent. HyDeploy hydrogen project reaching 20% blend . 2020 https://cadentgas.com/news-media/news/january-2020/hydeploy-hydrogen-project-reaching-20-blend.
69. SGN. H100 Fife. https://www.sgn.co.uk/H100Fife (2020).
70. Xoserve. Xoserve Search. https://www.xoserve.com/xoserve-search?term=scotland off gas.
71. Scottish Government. Scottish Government Green House Gas Statistics Spreadsheet. https://www.gov.scot/binaries/content/documents/govscot/publications/statistics/2020/06/scottish-greenhouse-gas-emissions-2018/documents/scottish-ghg-dataset-2018/scottish-ghg-dataset-2018/govscot%3Adocument/scottish-ghg-dataset-2018.xlsx.
72. Scottish Government. Ferry Routes 2018. (2018).
73. OpenStreetMap. Extract from OpenStreetmap 2020, manual exrcise to attribute whether line is Electrified. https://download.geofabrik.de/europe/great-britain/scotland.html (2020).
74. Transport Scotland. Shapefile from Transport Scotland. https://www.spatialdata.gov.scot/geonetwork/srv/eng/catalog.search;jsessionid=2628785CBF1685274A4DF67009EF9833#/metadata/%7B2c86562d-8183-48e8-a8ee-41066422be51%7D.
75. Department for Transport Statistics. Vehicle Licensing Statistics. (2019).
76. Global Railway Review. Scotland's ambition to deliver a decarbonised rail network. https://www.globalrailwayreview.com/article/94837/michael-matheson-scotland-rail-decarbonisation/ (2020).
77. Scottish Government. Energy Statistics Database. https://www2.gov.scot/Topics/Statistics/Browse/Business/Energy/Database (2019).
78. SEPA. Scottish Pollutant Release Inventory. https://www.sepa.org.uk/environment/environmental-data/spri/ (2019).
79. OGUK. OGUK Pathway to a Net-Zero Basin: Production Emissions Targets Report 2020. https://oilandgasuk.cld.bz/OGUK-Pathway-to-a-Net-Zero-Basin-Production-Emissions-Targets-Report-2020/2/ (2020).
80. Energy Vice. Malternative Energy – Giving a dram about decarbonisation - News for the Oil and Gas Sector. https://www.energyvoice.com/otherenergy/211376/malternative-energy-giving-a-dram-about-decarbonisation/ (2019).
81. SSE. Peterhead Power Station. https://www.ssethermal.com/flexible-generation/peterhead (2019).
82. Scottish Government. Scottish Energy Statistics Hub. https://scotland.shinyapps.io/Energy/?Section=RenLowCarbon&Subsection=RenElec&Chart=RenElecTarget (2019).
83. Scottish Renewables. Renewable Energy Facts & Statistics | Scottish Renewables. https://www.scottishrenewables.com/our-industry/statistics (2019).

84. Energy Research Partnership. Potential Role of Hydrogen in the UK Energy System ERP . Energy Research Partnership https://erpuk.org/wp-content/uploads/2016/10/ERP-Hydrogen-report-Oct-2016.pdf (2016).
85. Burke, J. & Rooney, M. Fuelling the Future Hydrogen's role in supporting the low-carbon economy. https://policyexchange.org.uk/wp-content/uploads/2018/09/Fuelling-the-Future.pdf.
86. GSTC. Grangemouth Refinery Hydrogen Plant. https://www.globalsyngas.org/resources/world-gasification-database/grangemouth-refinery-hydrogen-plant (2020).
87. ExxonMobil. Your guide to the Fife Ethylene plant. https://mossmorran.org.uk/wp-content/uploads/2017/07/FEP_brochure.pdf (2010).
88. BOC. Kittybrewster Aberdeen: Europe's largest hydrogen vehicle refueling station . https://www.boconline.co.uk/en/images/Case study Kittybrewster Aberdeen hydrogen refuelling station_tcm410-563229.pdf (2019).
89. Aberdeen City Council. Refuelling station launched as Aberdeen leads the way in hydrogen technology. https://news.aberdeencity.gov.uk/refuelling-station-launched-as-aberdeen-leads-the-way-in-hydrogen-technology/ (2017).
90. Arup. Decommissioning in the North Sea - Arup. https://www.arup.com/perspectives/publications/research/section/decommissioning-in-the-north-sea (2014).
91. Oil and Gas Authority. The Maximising Economic Recovery Strategy for the UK As reproduced by the OGA Introduction 5. https://www.ogauthority.co.uk/media/3229/mer-uk-strategy.pdf (2015).
92. Scottish Goevernment. Binaries Content Document. 2 https://www.gov.scot/binaries/content/documents.
93. Oil & Gas Authority. UK Oil and Gas Reserves and Resources as at end 2018. https://www.ogauthority.co.uk/data-centre/data-downloads-and-publications/production-projections/ (2018).
94. Oil and Gas Authority. February 2020 Update of OGA Projections of UK Oil and Gas Production and Expenditure. https://www.ogauthority.co.uk/media/6406/oga-medium-term-projections-feb-2020.pdf (2018).
95. Chapter 4 Natural Gas. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/820685/Chapter_4.pdf (2020).
96. HMO UK Goverment. Digest of UK Energy Statistics (DUKES). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/840015/DUKES_2019_MASTER_COPY.pdf (2019).
97. Scottish Government. Scotland's Marine Atlas: Information for The National Marine Plan - gov.scot. https://www.gov.scot/publications/scotlands-marine-atlas-information-national-marine-plan/pages/49/ (2011).
98. SSE Renewables. Berwick Bank and Marr Bank (formerly Seagreen 2&3) . https://www.sserenewables.com/offshore-wind/projects/berwick-bank-and-marr-bank-formerly-seagreen-2-3/.
99. BBC NEWS. SSE Renewables to build first subsidy-free wind farm - BBC News. https://www.bbc.co.uk/news/uk-scotland-highlands-islands-51325543 (2020).
100. Offshore Wind Scotland. Offshore Wind Scotland: Renewable Wind Energy in Scotland. https://www.offshorewindscotland.org.uk/ (2020).
101. Scottish Government. Draft offshore wind policy statement: consultation . https://www.gov.scot/publications/draft-offshore-wind-policy-statement/pages/2/ (2019).

102. Scottish Government. Offshore wind energy: draft sectoral marine plan. https://www.gov.scot/publications/draft-sectoral-marine-plan-offshore-wind-energy/ (2019).
103. Crown Estate Scotland. Crown Estate Scotland - Media centre - News, media releases & opinion - ScotWind leasing - update on timescales and next steps. https://www.crownestatescotland.com/media-and-notices/news-media-releases-opinion/scotwind-leasing-update-on-timescales-and-next-steps (2019).
104. UK Government. Contracts for Difference (CFD) Allocation Round One Outcome . https://www.gov.uk/government/publications/contracts-for-difference-cfd-allocation-round-one-outcome (2015).
105. UK Government. Contracts for Difference (CfD) Allocation Round 3: results . https://www.gov.uk/government/publications/contracts-for-difference-cfd-allocation-round-3-results (2019).
106. Joos, M. & Staffell, I. Short-term integration costs of variable renewable energy: Wind curtailment and balancing in Britain and Germany. Renewable and Sustainable Energy Reviews vol. 86 45–65 (2018).
107. National Grid. Network route maps | National Grid ET. https://www.nationalgrid.com/uk/electricity-transmission/network-assets/network-route-maps (2020).
108. The Scottish Government. Scotland's Electricity and Gas Networks: Vision to 2030. (2019).
109. Scottish Government & The British Geological Survey. Opportunities for CO2 Storage around Scotland - an integrated strategic research study. https://www.sccs.org.uk/images/expertise/reports/opportunities-for-co2/CO2-JointStudy-Full.pdf (2009).
110. British Ports Association. Scottish Ports. http://www.scottishports.org.uk/ (2020).
111. Acorn. Project: ACT Acorn Feasibility Study Terms of Use. www.actacorn.eu.
112. Fastflow. Case Study: St Fergus Gas Terminal Asset Health . (2018).
113. INEOS. Welcome to INEOS Grangemouth. https://www.ineos.com/globalassets/ineos-group/grangemouth/about/ineos-grangemouth-a5-visitor-welcome-bookletfinal-pdf.pdf.
114. The University of Edinburgh & Heriot-Watt University. (PDF) Hydrogen storage in porous geological formations-Onshore play opportunities in the Midland Valley (Scotland, UK). https://www.researchgate.net/publication/328225219_Hydrogen_storage_in_porous_geological_formations-Onshore_play_opportunities_in_the_Midland_Valley_Scotland_UK (2018).
115. British Geological Survey. Underground natural gas storage in the UK | Renewables and energy security at BGS | British Geological Survey (BGS). https://www.bgs.ac.uk/research/energy/undergroundGasStorage.html (2020).
116. IOGP. The potential for CCS and CCU in Europe REPORT TO THE THIRTY SECOND MEETING OF THE EUROPEAN GAS REGULATORY FORUM 5-6 JUNE 2019 COORDINATED BY IOGP. https://ec.europa.eu/info/files/31st-madrid-forum-conclusions-workshop_en (2019).
117. Hydeploy. Hydeploy Website. https://hydeploy.co.uk/.
118. German Federal Government. The National Hydrogen Strategy (Germany). https://www.bmbf.de/files/bmwi_Nationale Wasserstoffstrategie_Eng_s01.pdf (2020).
119. European Commission. COMMITTEE AND THE COMMITTEE OF THE REGIONS A hydrogen strategy for a climate-neutral Europe. https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf (2020).

120. FCH, E4Tech, Ecorys & Strategic Analysis. Value Added of the Hydrogen and Fuel Cell Sector in Europe Supporting European growth and competitiveness Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies . https://www.fch.europa.eu/page/FCH-value-chain (2019).

121. VDMA. Fuel Cell Industry Guide Germany:2016.

122. E4Tech. E4tech Development of a roadmap for hydrogen and fuel cells in the UK to 2025 and beyond.

123. E4Tech. E4tech Assessment of the Swiss hydrogen and fuel cell sector.

124. Office of National Statistics. UK National Accounts, The Blue Book time series - Office for National Statistics. https://www.ons.gov.uk/economy/grossdomesticproductgdp/datasets/bluebook (2019).

125. European Commission. EU H2020 TRL. https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf (2015).

Scottish Government
Riaghaltas na h-Alba
gov.scot

Scottish Enterprise

HIE

ARUP