Rail Cluster Project

Hydrogen's Role in Decarbonisation: Developments in Rail Traction and the Wider Ecosystem

October 2021

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This paper was written in collaboration with the Hydrogen Accelerator at the University of St Andrews. A special thanks to Fiona Landy and Maarten Verbraeken for their support.

Funded by Transport Scotland, the Hydrogen Accelerator brings together government, businesses and researchers and is enabling effective and efficient implementation of hydrogen technologies into Scotland, supporting economic growth in this important low carbon sector. For more information - https://h2-accelerator.org/.

Rail Cluster Project

The Rail Cluster Builder project was awarded to Scottish Engineering in August 2020 and is an 18-month programme funded by Scottish Enterprise and supported by Transport Scotland. The purpose of the project is to facilitate connections for SMEs in the engineering and manufacturing sectors in Scotland seeking to diversify into the rail market or grow their existing business in rail.

The project is jointly funded by Scottish Enterprise and the 2014 – 2020 European Structural and Investment Fund through SPRITE (Scottish Programme for Research, Innovation and Technology Ecosystem). This is a small programme which aims to improve the innovation performance of Scotland's Small and Medium Sized Enterprises (SMEs) and stimulate greater coordination between stakeholders and partner organisations to help businesses capitalise on new economic and public sector innovation opportunities.

The roots of the rail cluster project lie in the Rail Services Decarbonisation Plan through which the Scottish Government aims to decarbonise passenger rail services in Scotland by 2035, ahead of the UK's target of 2040. These targets present a real challenge to the industry and its supply chain, requiring a massive uplift in the electrification programme, new efficient train fleets powered by electricity, battery and hydrogen to replace diesel, and innovations and efficiencies to deliver this transformation whilst keeping rail transport affordable for taxpayers and users.

This presents real opportunities for Scottish engineering and manufacturing SMEs with the potential creation of new skilled, sustainable employment. The Rail Cluster Builder will support SMEs in establishing their presence in rail and help develop Scotland as a leader in the innovation and manufacture of net zero rail products and services. Decarbonisation of our railways is not the end of the story, but it is the key to unlocking the potential of the future 'world 'class rail transportation network envisaged by Government, offering greater connectivity and accessibility, better service, and faster travel times the length and breadth of the UK, and encouraging modal shift from road and air transport.

1 Introduction

In two of our previous reports, (the **Electrification paper, January 2021** and the **Market Insights report, March 2021**) we explored hydrogen as an alternative traction solution to electrification in the journey to net zero emission targets set by both the Scottish and UK Governments. This report is a continuation of those previously issued and focuses on hydrogen train development and the rationale behind a hydrogen economy to support the potential use of hydrogen trains as well as other hydrogen innovations in various sectors across the country.

We have used publicly available resources to form the basis of this report as well as significant input from the Hydrogen Accelerator at the University of St Andrews to compile an insight report into the potential use of hydrogen in the rail sector and the wider hydrogen industry for our rail cluster SME community. The overall aim of this report as with others is to raise awareness, generate discussion and potentially spark new ideas of innovations to support the Rail Decarbonisation Action Plan.

The **UK Government's Hydrogen Strategy** outlines how the UK rail industry can be supported through the development of hydrogen economies and continue to position itself as one of the 'greenest' forms of travel. The strategy aims to commit to its net zero target for 2050 as well as to decarbonise unelectrified parts of the rail network through electric trains and in areas where it makes economic and operational sense, the use of alternative traction technologies such as battery and hydrogen trains will be introduced.

The Scottish Government issued the **Rail Decarbonisation Action Plan** in July 2020 with ambitious aims to run net zero passenger services by 2035 ahead of the UK targets. The Scottish Government also published a **Hydrogen Policy Statement** in December 2020 setting out a vision for the development of a hydrogen economy in Scotland and ambitions for renewable and low carbon hydrogen generation. Scotland has a key role to play in the development of a UK hydrogen economy with the potential to benefit from offshore and onshore wind resources and wave and tidal power as a source of the development of hydrogen. It also has existing key skills in the oil and gas, offshore wind and energy sectors. Scotland is home to a number of world leading hydrogen demonstration projects that are supporting the development of hydrogen as a source of green energy in the future.

The European Marine Energy Centre in the Orkney Islands has a £65m portfolio of renewable hydrogen projects based on its significant and innovative local renewable energy capacity. Aberdeen has a fleet of 25 hydrogen double decker buses and numerous other hydrogen fuelled vehicles across the city which has led to the development of the Aberdeen Hydrogen Hub initiative which seeks to become one of the key model hydrogen regions in Europe. The H100 neighbourhood trial project in Fife is installing 300 homes with new hydrogen boilers to demonstrate hydrogen for domestic heating.

2 The development of hydrogen train solutions

As we have noted in previous reports, Rail is recognised as one of the cleanest and greenest modes of transport. While this is the case, the industry continues to strive for solutions that drive less impact on the environment.

2.1 The world's first hydrogen train

The world's first hydrogen train powered by hydrogen fuel was produced by Alstom. Cordia iLint entered service in Germany in 2018 and was the world's first passenger train powered by a hydrogen fuel cell which produces electrical power for traction. This zero emission train emits low levels of noise with exhaust being only steam and condensed water. The Cordia iLint is now operational in Austria, Sweden and France with other countries either trialling or placing orders.

2.2 The UK's first hydrogen powered train and other developments

Hydrogen's Role in Decarbonisation: Developments in Rail Traction and the Wider Ecosystem

The UK's first hydrogen powered train known as HydroFLEX was developed by the University of Birmingham's Centre for Railway research and Education in partnership with Porterbrook and was launched in 2019. The HydroFLEX train has been developed from a Class 319 train and has been fitted with hydrogen fuel tanks, a fuel cell and battery pack to enable the train to operate with zero carbon emissions.

In 2019, Alstom and Eversholt Rail announced the development of a new hydrogen train for the UK market. Known as Breeze, the conversion of existing Class 321 trains to create a clean solution with no harmful emissions was confirmed. The Alstom facility in Widnes is managing the conversion of the Breeze trains, creating high quality engineering jobs.

In 2020, East Japan Railway Company (JR East), Hitachi and Toyota Motor company entered into an agreement to develop a hydrogen-electric train known as HYBARI. The three companies are collaborating to develop and test a new generation of train which will use hydrogen powered fuel cells and storage batteries as its source of electricity.

Deutsche Bahn (DB) and Siemens Mobility are also driving forward the climate-friendly transition in transport and are testing the use of hydrogen for rail for the first time. The aim is to test a completely new overall system consisting of a newly developed train and newly designed filling station. DB will refine one of its maintenance shops for servicing the hydrogen powered train.

2.3 Scotland's first hydrogen powered train

In Scotland, Arcola Energy and its industry partners are collaborating with Angel Trains to deliver Scotland's Zero Emission train project. A consortium of engineering and technology firms is building Scotland's first hydrogen powered train which is set to be ready for Glasgow's COP26 climate conference in November this year. The team is based at the Bo'ness and Kinneil Railway and is converting a ScotRail class 314 passenger train into a fully certified, hydrogen train which demonstrates that Scotland has significant capabilities in converting existing rolling stock. This fits with the just transition and the utilisation of existing assets for a circular green economy.

The consortium includes Scottish Enterprise, Transport Scotland, the University of St Andrew's Hydrogen Accelerator, Arup, Abbott Risk Consulting and AEGIS Certification Services to boost the Scottish rail supply chain and progress green technology in the sector. Angel Trains is supporting with rolling stock expertise, technical advice, parts, equipment, and an investment in green hydrogen refuelling infrastructure.

2.4 Summary

There is significant activity in the development of hydrogen trains across the globe, in Europe and in the UK. **Network Rail's Traction Decarbonisation Network Strategy** (TDNS) states the need for hydrogen to be a vital part of the GB railway system where electrification is not an option for geographical or economic reasons. Hydrogen trains could also offer a potential transition solution to decarbonise ahead of electrification. Of note too is the fact that hydrogen production and fuelling stations can also be used for other modes of transport such as buses, taxis, road fleets etc and so the next part of this report is focused on the wider application of hydrogen across the country as well as a focus on hydrogen production, storage, refuelling etc and the synergies across various industry sectors.

3 Vision for Scotland

For the future low carbon energy system in Scotland, there will certainly be an increase in electrification, although additional energy carriers will be required to enable the development of a resilient and integrated 'whole energy' system. Hydrogen will play a pivotal role in moving to this low carbon future. Due to its high energy density and good storage properties hydrogen can be used to decarbonise sectors that can't be powered by electricity alone. This includes large transport vehicles like trucks, trains or buses and heavy industry or high temperature industrial processes.

Why hydrogen?

Hydrogen is a clean alternative to natural gas, as it emits no carbon dioxide at the point of use. However, while hydrogen is found pretty much everywhere on our planet, it's rare in gas form. This means that it has to be manufactured to be used as fuel. There are two principal ways it can be produced as a gas. These different processes produce what is known as 'green' and 'blue/grey' hydrogen.

Green hydrogen is made when a renewable electricity source, like an onshore wind farm, is used to generate the electricity to power an electrolyser which splits water into its two elements - hydrogen and oxygen. Green hydrogen is a zero emissions fuel that offers a long term, sustainable alternative to fossil fuels.

Grey hydrogen uses natural gas to react with steam to form hydrogen and is considered a high carbon fuel. Most hydrogen currently produced globally is high carbon. One possible way to make grey hydrogen a low carbon fuel is through the use of carbon capture, usage and storage (CCUS). This form of hydrogen is called 'blue' hydrogen. To meet our net zero targets, all future hydrogen production will need to be low carbon.

Scotland has vast natural resources which can be utilised to develop a thriving hydrogen economy. With the abundance of renewable energy generation, Scotland has the potential to produce sufficient green hydrogen for its domestic market but also for exporting internationally. Onshore and offshore wind, hydro, wave and tidal energy can all be drawn upon to produce hydrogen for a range of purposes, including transport, heating and for various industrial processes, such as steel or cement production, but also for the food & drinks sector. An example of such a hydrogen ecosystem which can be built in Scotland is shown in Figure 1.

The benefits of building a hydrogen economy in Scotland could be significant, aiding the development of Scottish supply chains and the creation of high value jobs and skills across many sectors. It also aligns with the Scottish Government's Climate Change target – to be net zero by 2045 – and their commitment to develop an inclusive, net-zero, green economy. Building on Scotland's existing infrastructure, skills and expertise, the development of domestic hydrogen production offers an opportunity to achieve the Scottish Governments aim of a 'just transition' away from reliance on fossil fuels and towards the goal of net zero and a transition which benefits all of Scotland's citizens.

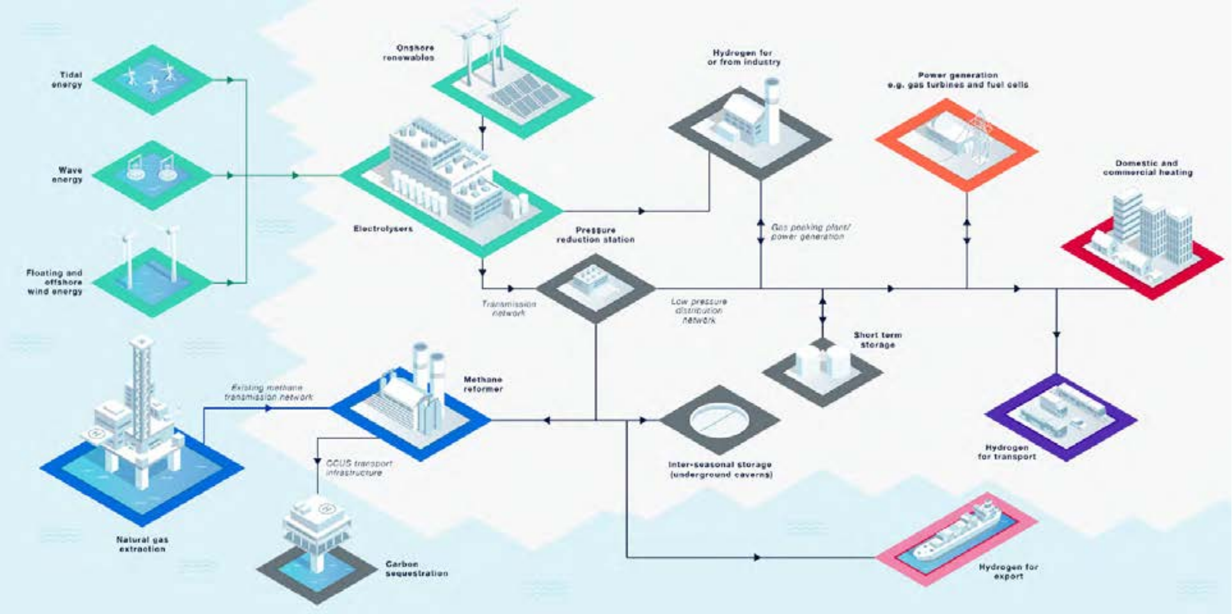

Figure 1: Example of hydrogen ecosystem, including hydrogen generation, storage, distribution and utilisation[1].

4 Hydrogen for Challenging to Decarbonise Sectors

While Scotland has made major advances in decarbonising its electricity grid, with consumption in 2020 97.4% covered by renewable sources, other energy sectors are arguably more difficult to decarbonise. These include domestic and commercial heating, heavy industry and transport. Whilst hydrogen may play a role in the decarbonisation of all of these sectors, it is currently recognised it has largest potential in (heavy-duty) transport.

4.1 Transport

It is recognised that transport contributes to more than a quarter of Scotland's greenhouse emissions. A significant proportion of this is from the road sector (cars, buses, vans and heavy-duty vehicles). It is estimated that in 1990 the emission of CO_2 from the road sector amounted to 9.3 MtCO2e (69% of total transport emissions) and this figure has been increasing annually. The Rail sector is in more of a positive position with around 76% of passenger and 45% of freight journeys already on electric traction and contributes around 1.2%, the lowest of all modes of transport.

Transport Scotland's National Transport Strategy for Rail details the continued investment in electrification and complementary traction systems (which could be hydrogen powertrains) to decarbonise the entire rail network (Figure 2). Hydrogen technologies could have a

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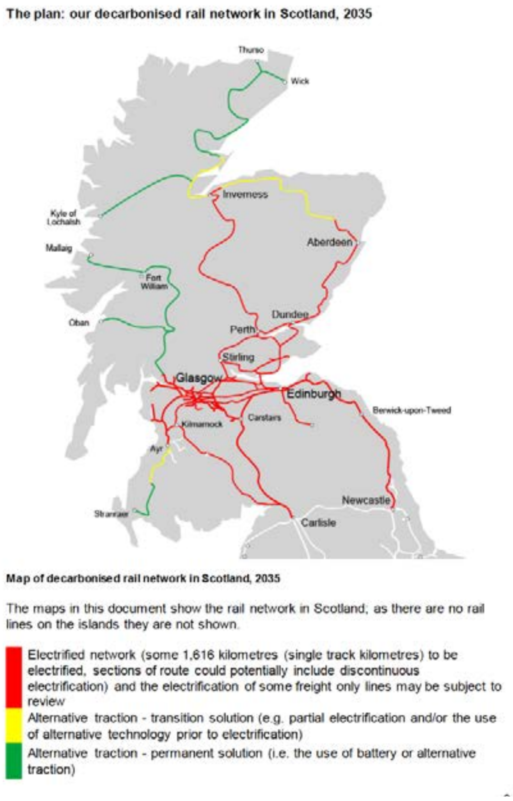
[1] Scottish Hydrogen Assessment, December 2020

significant role to play in supporting the rail sector's decarbonisation targets even where electrification is planned, providing fuel cell electric trains until electrification has been deployed.

The modal shift to utilising more public sector transport such as buses and rail for freight will assist in enabling Scotland achieving its decarbonisation targets.


The plan: our decarbonised rail network in Scotland, 2035

Map of decarbonised rail network in Scotland, 2035

The maps in this document show the rail network in Scotland; as there are no rail lines on the islands they are not shown.

- 🟥 Electrified network (some 1,616 kilometres (single track kilometres) to be electrified, sections of route could potentially include discontinuous electrification) and the electrification of some freight only lines may be subject to review
- 🟨 Alternative traction - transition solution (e.g. partial electrification and/or the use of alternative technology prior to electrification)
- 🟩 Alternative traction - permanent solution (i.e. the use of battery or alternative traction)

Figure 2: Transport Scotland's plans for a decarbonised rail network by 2035.

5 The Hydrogen colour palette

Whilst using hydrogen as a fuel is zero-emission at its point of operation, with only water as its product, its overall well-to-wheel carbon footprint is largely determined by its method of production. Indeed, when derived from fossil fuels, over its lifecycle it may have worse greenhouse gas (GHG) emissions than if one were to use those fossil fuels directly.
To understand the impact of hydrogen production methods and their embedded GHG emissions, the hydrogen colour palette was devised as a means to distinguish between carbon intense and low or effectively zero carbon sources of hydrogen.

Grey hydrogen

Currently, the vast majority (around 95%) of the world's hydrogen is derived from natural gas, through a process called steam methane reforming (SMR). This process combines natural gas (essentially methane) and steam to produce syngas, a combination of carbon monoxide and hydrogen, see reaction 1. The carbon monoxide can then be converted to yield additional hydrogen via the water-gas shift reaction (2), which also generates a molecule of carbon dioxide, CO_2. The process is endothermic, so requires heat provided by burning fossil fuels, leading to additional carbon emissions. Further GHG emissions are caused by accidental leakages of methane upstream, which can be significant, particularly when considering methane's potent GHG effect, around 40 times that of CO_2.

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad 1$$

$$CO + H_2O \rightleftarrows CO_2 + H_2 \qquad 2$$

$$4CH_4 + O_2 + 2H_2O \rightarrow 4CO + 10H_2 \qquad 3$$

A related process, auto-thermal steam reforming (ATR), combines partial oxidation and SMR and leads to a similar amount of CO_2 released as part of the chemical process (reaction 3). However, it is significantly less endothermic and thus result in slightly reduced carbon emissions from process heating. Overall GHG emissions (expressed in kg CO_2 equivalent) for SMR and ATR are 9.2 – 11 kg CO_2e / kg H_2.[2]

Blue hydrogen

Blue hydrogen is essentially identical to grey hydrogen, with the exception that carbon capture, (utilisation) and storage (CCS or CCUS) is applied post-process to reduce CO_2 emissions. High rates of CCS can only be achieved if post combustion CO_2 is also captured. This is more difficult than capturing reaction CO_2 and SMR can therefore only achieve around 90% capture, whereas ATR is reported to be capable of reaching 98% capture rates. These rates do not include emissions arising from the CCS process itself and accidental methane leakages still contribute to GHG emissions as well. The ultimate capture rates are also likely to be determined by economics as opposed to technical feasibility and as such will be driven by government policy. A best-case scenario for emissions from 'blue hydrogen' still results in 1.5 – 3.9 kg CO_2e / kg H_2.[2]

Green hydrogen

Utilising surplus renewable electricity to electrolyse water is a method which is truly zero-carbon from an operational point of view and its product is therefore coined 'green hydrogen'. Its only by-product is oxygen, which is usually vented to atmosphere, but may be collected as it has economical value for instance in medical use or wastewater treatment plants. The UK and Scotland in particular are ideally suited to be producers of green hydrogen, thanks to an

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[2] Hydrogen decarbonization pathways, A life-cycle assessment, January 2021, www.hydrogencouncil.com

abundance of renewable energy sources and relatively small domestic electricity demand from its small population. Production of green hydrogen is thus actively pursued by the Scottish Government as a vehicle to decarbonise various sectors and as a potential export product. It is also integral to Scotland's 'Just Transition', utilising existing skills and expertise from the oil & gas industry to create green jobs for the renewable sector. A lifecycle analysis suggests that the well-to-wheel GHG emissions are currently lowest for hydropower based electrolysis (0.3 kg CO_2e kg H_2), followed by wind (0.5) and solar (1.0), due to emissions associated with manufacture of turbines, solar panels, etc. [2]

6 Large scale production of green hydrogen

Although green hydrogen is currently seen as expensive, in particular when compared to grey and blue hydrogen, this is cost difference is mainly due to economies of scale, which currently do not exist for green hydrogen. Steam methane reforming is an industrially mature technology and produces hydrogen at good efficiencies, in particular when well-integrated with other chemical processes. The cost of producing hydrogen in this way is therefore low, around £1/kg. Applying CCUS to this method of hydrogen production increases the cost to just below £2/kg. The main operational cost for producing green hydrogen is the cost of green electricity, leading to an overall cost around £5/kg, although higher estimates exist, which are related to high capital expenditure for green hydrogen equipment. As shown in Figure 3, the cost of green hydrogen is expected to fall over the next 30 years to become competitive with blue hydrogen, a reduction which is due to scaling up production leading to economies of scale for both renewable electricity and hydrogen production equipment, such as electrolysers, compressors and storage tanks.

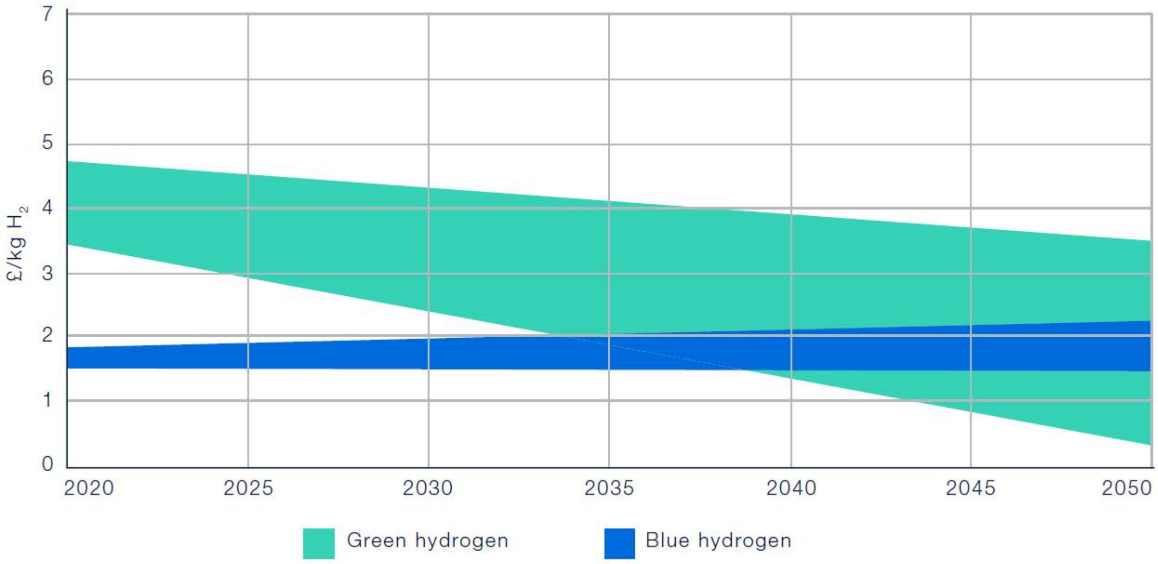

Figure 3: Projected costs of different forms of hydrogen, showing green hydrogen becoming cost competitive in the early 2030s. Grey hydrogen costs around £1/kg but will not be a viable source of hydrogen due to its adverse environmental effects[3].

Scotland has great potential for large scale production of green hydrogen, due to an abundance of renewable energy potential. **Error! Reference source not found.** shows the wind potential in Europe in terms of capacity factor (average power output relative to nominal turbine power), where onshore sites range from 30 – 50%, whereas offshore can reach into the high 60s. Currently, there is already 10.9 GW of onshore and 1.0 GW of offshore wind installed, with a further 9.0 and 9.5 GW of onshore and offshore wind planned to come online by 2030, respectively. Additional rounds of site leases by the Crown Estate should add another 8 – 10 GW of offshore wind in the early 2030s. At this point in time, it is anticipated that 1 – 2 GW of wind will be installed each year, totalling ca. 50 – 60 GW by 2040. Tidal and wave energy technology are not as mature as wind yet, so current projections are for 1 GW of tidal to be installed around 2035 and 1 GW of wave by 2040[4,5,6]. Assuming a pessimistic capacity factor of 30% for these renewable sources (as discussed, floating offshore wind may achieve over 60%, see **Error! Reference source not found.**), this would generate around 160 TWh per year, equal to Scotland's current total energy demand. However, thanks to efficiency improvements and behavioural changes, energy demand is expected to reduce by 5 – 28% to 110 – 148 TWh by 2050[7], with up to 47% of the energy demand from electricity use, leaving ample generation capacity to generate hydrogen for hard to decarbonise sectors, such as transport and heavy industry. With increased use of alternative green technologies in Scotland, such as heat pumps for domestic heating and

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[3] Scottish Hydrogen Assessment, December 2020

[4] Scottish Hydrogen Assessment, December 2020

[5] www.scottishrenewables.com

[6] www.offshorewindscotland.org.uk

[7] Scottish Energy Strategy: The future of energy in Scotland, December 2017

solar PV for residential electricity, this would leave the potential for green hydrogen generation for export as well. Native demand for hydrogen is expected to be below generation capacity, whereas the situation is expected to be reversed for other countries, such as Germany and Japan.

To effectively harness offshore wind in deeper waters, that is, sites further away from the coastline, floating offshore wind farms will be required. This technology is less mature than fixed foundation offshore or onshore wind and therefore still in development, much like water electrolysis. Some of the key challenges facing floating offshore wind centre around manufacture, such as materials choice and cost-effective manufacturing thereof. Infrastructural issues exist as well, relating to port availability for assembly, repair and maintenance and cost-effective electrical connections. These challenges mean that floating offshore wind is still considered too costly in comparison with onshore and fixed offshore wind, but the increasing need for renewable electricity and green hydrogen is likely to force adoption and costs are expected to fall with scaled up deployment.

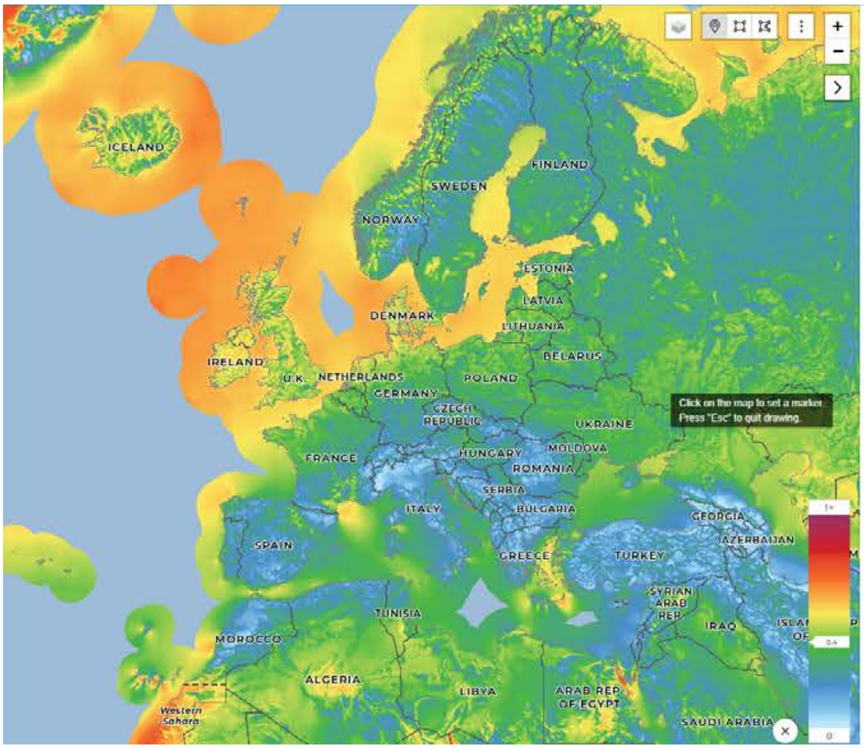

Figure 4: Wind capacity factors for Europe, showing Scottish offshore site should be capable of averaging > 60% (source: https://globalwindatlas.info)

7 Research and innovation

Research and innovation are actively pursued in many areas relating to hydrogen which can broadly be divided into the following categories:

- Hydrogen generation
- Hydrogen utilisation

- Hydrogen distribution
- Hydrogen storage

When focussing on hydrogen in transport, additional fields of interest become relevant, such as battery technology, power electronics, duty cycle modelling, control systems, and so on. We will give a brief overview of these.

7.1 Hydrogen generation

Due to the Scottish and UK governments' focus on pursuing net zero emission technology, the production of hydrogen needs to address any carbon emissions associated with it. Currently, the majority of hydrogen produced globally is through a process called steam methane reforming, which utilises natural gas as the reactant. It is associated with high greenhouse gas emissions, notably CO_2 as a by-product of the chemical reaction, but also methane due to accidental leakages in the supply chain. Hydrogen produced by this method is termed 'grey hydrogen' and results in overall emissions of 9.2 – 11 kg CO_2e / kg H_2.

Figure 5: Steam methane reforming plant in Dormagen, Germany

Considerable research effort has been invested over the last decade or so to 'clean' this process by capturing the CO_2 from the product stream, rather than venting it to atmosphere, creating so-called 'blue hydrogen'. Despite being technologically feasible, by feeding the effluent product stream through either amine scrubbers or columns packed with solid adsorbents, due to cost, carbon capture has rarely been used at industrially relevant scales. Capture rates can be as high as 90%, but only if post-combustion CO_2 (emitted as a result of heating the endothermic process) is captured as well as reaction CO_2. Additionally, the problem from accidental methane leakages upstream remains and being a greenhouse gas 40 times as potent as CO_2, this can significantly contribute to global warming. Depending on the method of reforming and extent of carbon capture, blue hydrogen has overall emissions of 1.5 – 3.9 kg CO_2e / kg H_2.

Research activity in Scotland covers many aspects concerning carbon capture, including the capture process, storage, utilisation and materials science. Developments in the carbon capture process covers direct air capture, process design, optimisation and intensification, and novel separation techniques, such as membrane separation. Research in storage may for instance focus on geological storage in offshore sites. Electrolysis of CO_2 with subsequent Fischer-Tropsch reactions to generate synthetic fuels is one approach towards CO_2 utilisation. Finally, there is a strong pedigree in developing new materials for use in the capture process (adsorbents, membrane materials) as well as for CO_2 electrolysis. A comprehensive overview of Scottish research activities can be found on the Scottish Carbon Capture & Storage website[8]. A major pilot project, Acorn, is also underway at St Fergus gas terminal in Aberdeenshire, which aims to generate blue hydrogen using offshore natural gas. Capture CO_2 will be piped/shipped to offshore geological storage sites[9].

Figure 6: Multiple pressure swing adsorption (PSA) columns for hydrogen purification. Vacuum PSA or temperature swing adsorption, which are related to the purification process, can also be used for carbon capture. Process CO_2 only accounts for 60 – 70% of the overall CO_2 emissions, the remainder being related to energy requirements for the process.

Utilising surplus renewable electricity to electrolyse water is a method which is truly zero-carbon from an operational point of view and its product is therefore coined 'green hydrogen'. Its only by-product is oxygen, which is usually vented to atmosphere, but may be collected as it has economical value for instance in medical use or wastewater treatment plants. The UK and Scotland in particular are ideally suited to be producers of green hydrogen, thanks to its abundance of renewable energy sources and relatively small domestic electricity demand from its small population. Production of green hydrogen is thus

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[8] https://www.sccs.org.uk/

[9] https://theacornproject.uk/

actively pursued by the Scottish Government as a vehicle to decarbonise various sectors and as a potential export product. It is also integral to Scotland's 'Just Transition' creating green jobs in the renewable sector by using existing skills and expertise from the oil & gas sectors, whilst at the same time levelling up the whole country by avoiding concentrating wealth. The distributed nature of green hydrogen production is well suited to address also this issue.

Whiteless Windfarm

ScottishPower's recent application for planning permission to develop a solar/battery powered green hydrogen production facility adjacent to their Whitelee windfarm 10 miles south of Glasgow provides a fascinating "real world" insight into the potential for commercial green hydrogen production in Scotland, and even more so as the city hosts the pivotal COP26 discussions. This development, the first to be built as part of the Green Hydrogen for Scotland partnership of ScottishPower, BOC, and ITM Power, will be the largest of its kind in the UK to date, and represents an important milestone in building a green hydrogen supply chain in Scotland.

The facility will house a 20MW electrolyser which will be able to produce up to 8 tonnes of green hydrogen per day. To put this figure in context, it is roughly equivalent to fuelling over 550 buses travelling from Glasgow to Edinburgh and return each day. The electrolysis process will be powered by a 40MW solar farm consisting of 62,000 solar cells, combined with a 50MW battery energy storage scheme. Both the battery and solar facilities are also components of the planning application. The choice of location will also allow these new developments to benefit from shared infrastructure and grid connection with the adjacent windfarm.

The hydrogen fuel produced at Whitelee will support local authorities, industries and transport operators in achieving their net zero targets, for example in public transport and heavy freight where hydrogen has an advantage due to its greater energy density versus battery.

For more information -
https://www.scottishpower.com/news/pages/green_hydrogen_for_glasgow.aspx.


Figure 7: Alkaline electrolyser stack at Akzo Nobel[10]

Despite having been used commercially for circa a hundred years, electrolysis is still a relatively immature technology without the benefits of economies of scale. This means that both capital and operational expenses associated with it are currently high, driving up the price of green hydrogen. Commercial hydrogen production by electrolysis is currently dominated by two technologies, alkaline and proton exchange membrane (PEM) electrolysis. Whilst relatively little research and development is being invested in alkaline electrolysis, PEM electrolysis is still developing, with research focusing on improving efficiency, durability and overall economics. PEM electrolysis utilises precious metals, such as platinum and iridium, as the electrocatalysts making the stacks expensive and so reducing the amount required, without affecting stack performance is key for this industry. Other electrolysis technologies are under development, such as anion exchange membrane electrolysis (AEM) and solid oxide electrolysis (SOE). The latter operates at high temperatures (typically 500 – 800°C), which allows for the use of cheaper catalysts as well as being capable of achieving 100% electrical efficiency. If using process waste heat to heat the cells, this has the potential to drastically improve the economics of green hydrogen production. Materials development and integration to ensure long-term durability is a key challenge for high temperature electrolyser cells.

8 Hydrogen utilisation

As is clear from the preceding text, hydrogen has use as a fuel in many applications. It can achieve this in a number of ways, either by direct combustion, electrochemical oxidation or conversion into different fuel, which may be easier to transport and store.

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[10] https://www.h2-international.com

8.1 Hydrogen for electricity generation

Fuel cells are essentially electrolysers operated in reverse mode. They combine hydrogen and oxygen from air to generate electricity. This is an electrochemical conversion process and thus avoids mechanical work from thermal energy, which is typical of combustion technologies, leading to much higher efficiencies. In analogy with electrolyser technologies, several fuel cell technologies exist, which are characterised by their ion conducting electrolyte. Depending on this, the technologies vary in operating temperature, materials selection and fuel capability. PEM (proton exchange membrane) fuel cells are currently the fuel cell of choice for transport applications, due to their relatively light weight, resilience to vibration and low operating temperature (60 – 80°C). Their electrolytes are polymer based (perfluorosulfonic acid) and can suffer from mechanical failure, particularly upon ageing. Electrodes contain platinum catalyst which require high purity hydrogen[11, 12] to avoid contamination rendering the fuel cells/stacks inoperable.

Other fuel cell types include alkaline, phosphoric acid and solid oxide and these are typically aimed at stationary power production. Alkaline fuel cells operate at a similar temperature as PEM fuel cells, but can use cheaper electrode materials, due to the alkaline nature of the electrolyte. This also means they do not suffer as much from high electrode overpotentials, resulting in higher electrical efficiencies. Challenges are the corrosive liquid electrolyte which is prone to 'poisoning' by CO_2, leading to carbonate formation and electrode deactivation. They therefore require either a CO_2 scrubber when operating in ambient air, or pure oxygen as the oxidant, adding to system complexity and cost. Phosphoric acid and solid oxide fuel cell operate at higher temperatures, making them more tolerant towards fuel impurities. A major challenge for PAFC is the highly corrosive electrolyte. SOFC are ceramic cells which operate at 500 – 1000°C, allowing the use of cheaper electrode catalysts, such as nickel. The high operating temperatures however requires careful selection of materials to ensure mechanical and chemical compatibility and thus long-term stability. Lowering the operating temperature allows for higher electrical efficiencies, whilst imposing fewer thermal strains on the system. The higher operating temperatures as compared to other fuel cell technologies, however, offers the potential of combined heat and power (CHP) generation, allowing for overall system efficiencies up to 90%.

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[11] https://www.sae.org/standards/content/j2719_201109/
[12] https://www.iso.org/obp/ui/#iso:std:iso:14687:ed-1:v1:en

Figure 8: HEXIS Galileo 1000N 1 kWe CHP system installed at the University of St Andrews. The system utilises a solid oxide fuel cell stack

Scotland has particular research strengths in materials development for high temperature solid state fuel cell technologies. On a system level, fuel cells need to be integrated into power systems, e.g. an automotive powertrain. Arcola Energy is one of the UK's leading system integrators for mobile applications and are based in Dundee. They are involved in a number of Scottish projects, aimed at delivering Fuel Cell Electric double deck buses, refuse collection vehicles and a demonstrator train. In such integrated systems, understanding duty cycles of different vehicles is key in optimally designing aspects of the vehicles, such as battery and fuel cell size, as well as onboard hydrogen storage capacity. Researchers in Glasgow University have been working on developing modelling and simulation tools in this field. The role of fuel cells in stationary applications has thus far mostly been as backup power supply or delivering power to poorly connected areas, electrically, but with access to gas supply.

8.2 Hydrogen for heat

Domestic and commercial heating is one of the main culprits responsible for CO_2 emissions in the UK. Replacing natural gas by hydrogen is seen as one option to decarbonise heating, requiring an upgrade to boilers to be compatible with burning hydrogen. A trial project is underway in Fife, H100, aiming to install hydrogen boilers and heat 300 homes in Levenmouth with 100% hydrogen. Other alternative technologies will additionally be required and potentially more suited to decarbonise heating, such as ground source heat pumps, but hydrogen will likely be part of the mix. The previously mentioned fuel cell powered CHP units are also likely to contribute to decarbonising heating, and their modular design up to hundreds of kilowatts allows for use in commercial as well as domestic settings of various sizes.

Figure 9: Hydrogen boiler, capable of using 100% hydrogen as fuel (Baxi Heating)

8.3 Hydrogen for Synthetic fuels and Ammonia

For the most demanding transport and mobile applications, such as aviation and shipping, it is likely a fuel with a higher volumetric density than hydrogen is required. Liquid fuels, such as synthetic fuels and ammonia are the most likely candidates to fulfil this role, although across the globe some are pursuing liquid hydrogen as fuel too. Synthetic fuels can be synthesised using a mixture of carbon monoxide and hydrogen and performing Fischer-Tropsch reactions, yielding hydrocarbon of varying length, depending on process conditions and reactor types. Innovation in re-using carbon dioxide to be the feedstock for carbon monoxide through electrolysis is ongoing. When both carbon monoxide and hydrogen are produced by electrolysis/renewable energy, these can be feedstock for green synthetic fuels. Similarly, ammonia may be synthesised by combining hydrogen and nitrogen and when the hydrogen is green, this offers potential for green ammonia. Ammonia can be liquefied at relatively mild conditions and is thus a viable option as a hydrogen containing energy carrier. The established method of ammonia production is through the Haber-Bosch process, which itself is highly energy intense, due to the need for elevated reaction temperatures and pressures. Research activity is ongoing to find a process with milder conditions, such as electrochemical conversion. Ammonia can either be re-converted to hydrogen or potentially utilised directly as a fuel.

Figure 10: Haldor Topsoe green ammonia plant, being built in Saudi Arabia, capable of producing 650 tonnes a day.

9 Hydrogen distribution

Work is underway to understand the suitability of the current natural gas grid to be able to accommodate hydrogen for distribution and storage (line stacking). A trial is ongoing at Keele University, blending 20% H_2 into existing gas pipelines, to be directly utilised in cookers and domestic boilers. To achieve 100% hydrogen utilisation requires a better understanding of the impact hydrogen has on leak rates and in particular hydrogen embrittlement of steel pipes. Scottish Gas Network (SGN) is leading a consortium aiming to deliver 100% green hydrogen to 300 homes in Levenmouth for domestic heat (and 1000 homes during phase 2). Hydrogen will be generated by offshore wind/electrolysis and distributed by a gas network to the homes.

Distribution by shipping or rail may also be viable but is likely a matter of economics due to hydrogen's low density, even under compression.

Hydrogen is usually shipped in tankers but could be sent in pipelines. Hydrogen causes embrittlement of metal so would need to go in polyethylene pipes and these would need tighter seals than those for natural gas to prevent leakages. Shipping adds to the costs of use.

10 Hydrogen storage

Hydrogen storage can broadly be divided between physical and chemical storage. Physical storage includes compressed and liquefied hydrogen, whereas chemical storage involves materials that can reversibly incorporate hydrogen as part of their chemical structure.

10.1 Physical storage

For physical storage, the predominant way of storing hydrogen is by compression. Due to hydrogen's low density, depending on the application, this may require elevated pressures of 350 – 1000 bar. This is particularly the case for transport applications, where space comes at a premium. Compression is energy intense and requires specialist equipment adding to the cost of hydrogen systems. And where fast refuelling is desirable, cooling equipment may also be required, due to hydrogen's unusual negative Joule-Thomson coefficient causing temperature increases in hydrogen tanks during this process. The need for tanks that are able to withstand high hydrogen pressures increases system weight, lowering the effective energy density of hydrogen. Research is therefore ongoing in finding lighter and stronger materials to use in the manufacture of tanks. Another active area of research is novel tank designs. Due to the high pressure inside tanks, they have been necessarily cylindrical in shape, which limits packing efficiency and essentially adds to overall system volume. Novel manufacturing techniques, such as additive manufacturing, may be able to help overcome (at least to a degree) the cylindrical shape constraint, meaning more efficient packing.

Figure 11: Type V hydrogen tank by Innovatus Technologies Ltd, using a novel design, with a claimed 10% gravimetric density

Liquefying hydrogen has the benefit of having a higher density than compressed hydrogen (~twice that of compressed at 700 bar), but it requires cooling to at least –240°C and its production is therefore highly energy intense. Due to the extremely low temperatures, leak rates tend to be significant, e.g. 1%/day. Additional safety concerns are involved when dealing with cryogenically cooled liquids, meaning that liquefied hydrogen is probably economically unviable for mainstream use, but it may find use as a storage medium in such applications as shipping where energy density is a premium.

10.2 Solid state storage

Solid state storage has been researched for many years, due to its potential to store hydrogen at greater volumetric densities. Generally speaking, in these materials, hydrogen is chemically or physically bonded within the solid, but can be reversibly released/stored upon pressure and temperature changes. Major challenges for solid state storage are gravimetric density, reversibility and reaction enthalpy. For automotive applications, gravimetric densities are required to be a minimum of 5.5 wt. %. Lightweight chemical hydrides (such as lithium and magnesium borohydrides) easily achieve this, even considering the overall system weight which would include storage tank, valves and regulators, but the hydrogen bonds are strong and thus desorption requires relatively high temperatures (325 – 450°C). This is additionally associated with large amounts of heat released/required during storage and desorption, up to 50 kWh for a tank holding 5 kg of hydrogen, causing major engineering challenges for short refuelling times. Poor heat transfer in the solid material further exacerbates this issue, as it would lead to local heating of the storage material during refuelling, limiting the effective amount of hydrogen which can be stored. Research is still active in finding material compositions which would balance amounts stored, desorption temperature and reaction enthalpies. Storing the hydrogen by way of physical bonds is an effective way to reduce adsorption/desorption enthalpies, but molecular hydrogen has few electrons and thus interacts very weakly with most solids. Solid state physical storage therefore often requires low temperatures or high pressures (but less extreme than for compressed/liquified hydrogen). Metal organic frameworks are an example of materials that store hydrogen by means of physical bonds, and research is ongoing to optimise these in terms of storage capacity and release temperature/pressure.

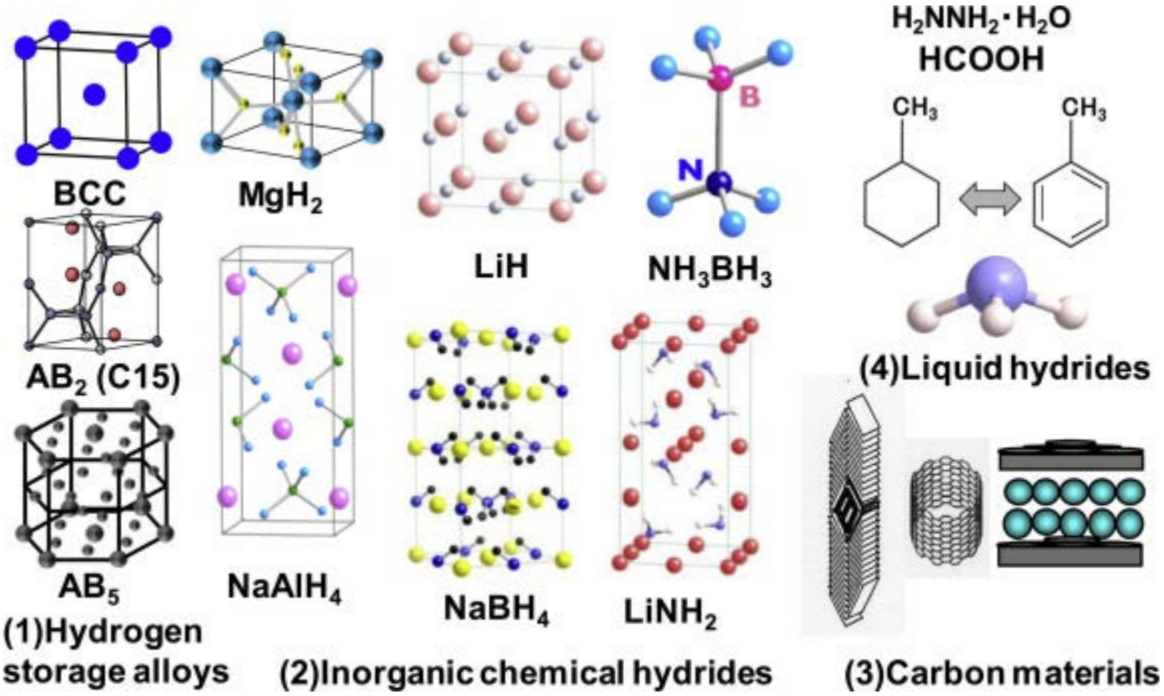

Figure 12: Various hydrogen storage materials, including ammonia and 'liquid hydrides'. The boundary between the latter and synthetic fuels is blurred.

11 Summary and Conclusions

Through the work of the Rail Cluster Builder we have explored the potential role of hydrogen fueled traction as a key component of the overall solution to decarbonisation of our railways, in particular as a transitional solution on the path to full electrification, and as a longer term solution in specific circumstances e.g. on those parts of the rail network where economic and physical factors make full electrification economically unviable.
In this technical paper we have reviewed progress in Scotland, the wider UK and internationally in developing hydrogen fueled rail traction solutions. We have also outlined the wider context of hydrogen utilisation i.e., the flexibility of the fuel and its synthetic derivatives as a means of supporting decarbonisation and reducing reliance on volatile hydrocarbon markets in a wide range of end uses including power generation, domestic and commercial heating, rail, road and sea transport, and even in air travel.

We have explored the hydrogen economy and associated ecosystem which will be required to generate, distribute and store hydrogen for use on our railways and other critical end uses. We have highlighted the critical role of green hydrogen whereby electrolysis-based production processes are powered by renewable energy sources thereby enabling the full potential of hydrogen as a vector for clean green energy, and we have explored some of the challenges and latest technical developments in the pursuit of more efficient and cost effective hydrogen supply chains.

Our main conclusions from this analysis are as follows:

- The Hydrogen economy is no longer a future concept - it is real and developing now, from its roots in demonstration projects, trials and R&D, and has the potential for rapid growth and improving commercialisation through economies of scale, synergies across multiple end-users, technical innovation, and government policy support.
- The UK, and Scotland in particular, has a comparative advantage in the development of the hydrogen economy as a result of our relative abundance of renewable energy resources, actual and planned, and the critical combination of commercial and academic technical expertise.
- It is most notable that SME businesses, often in partnership with academia, are at the very forefront of development in the Hydrogen sector, where their vision, agility and innovation skills can be deployed to maximum competitive advantage.
- Overall, the scale and scope of the investment required to take full advantage of hydrogen places it as one of the major industrial challenges and opportunities emerging for Scotland and crosses multiple supply chains in manufacturing and engineering.
- The Rail Cluster team will continue to monitor developments in the hydrogen sector, with a primary focus on rail but also on developments in hydrogen; production and supply chains and in synergistic transport related sectors.