


# A REVIEW OF HOW THE MIDLANDS REGION CAN SUPPORT GREEN HYDROGEN PRODUCTION, AND THE IMPORTANCE OF A HOLISTIC APPROACH

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## DEFINITIONS

**GHG**
Greenhouse Gas

**NATURAL GAS**
Methane Gas ($CH_4$)

**SUPPLY CHAIN**
A logistical chain of goods or the sequence of processes that make up the manufacture or distribution of a product.

**GROSS VALUE ADD (GVA)**
A metric used to show how much a given sector contributes to the economy and is widely accepted as an economic productivity metric [1].

**GREY HYDROGEN**
Hydrogen is produced using methane, most commonly via steam methane reforming (SMR), which results in greenhouse gas (GHG) emissions released into the atmosphere.

**BLUE HYDROGEN**
Manufactured in the same way as grey hydrogen, it uses carbon capture, utilisation, and storage (CCUS) to mitigate GHG emissions.

**GREEN HYDROGEN**
Where an electric current splits water into hydrogen and oxygen gas, in a process called electrolysis, using renewable electricity. If renewable electricity is used, the whole process results in zero GHG emissions.

**RTOs**
Research and Technology Organisations, "RTOs innovate to improve your health and well-being, your safety and security, your mobility and connectivity. RTOs' technologies cover all scientific fields. Their work range from basic research to new products and services development. RTOs are non-profit organisations with public missions to support society. To do so, they closely cooperate with industries, large and small, as well as a wide array of public actors." [2]

1 Glossary is Statistical Terms. Gross Value Added. [Online] 25 10 2001. [Cited: 17 02 2022.] https://stats.oecd.org/glossary/detail.asp?ID=1184.
2 EARTO. RTOs – Research and Technology Organisations. [Online] 2022. [Cited: 25 04 2022.] https://www.earto.eu/about-rtos/.

## EXECUTIVE SUMMARY

The ever-increasing need to decarbonise human activity is transforming the global energy landscape, with economies around the world incorporating low carbon technologies into their energy mixes. The UK was one of the first major economies in the world to put 'net-zero by 2050' into law, and since doing so in 2019, emissions have decreased year-on-year [1]. The significance of 'net-zero by 2050' has become globally realised, with an increasing number of countries defining their net-zero strategies. Although many have plans in place, the pathway is foggy, and reaching this goal is still uncertain. Meeting the target will require a fundamental change across the global economy, integrating sustainable technologies which are likely to reshape society's relationship with energy consumption.

Electrification is possible in a range of applications that underpin day-to-day life and was the first step in a global move away from fossil fuels. It stands to reason that anything which can be easily electrified, should be electrified, but for some sectors this is difficult, due to either high thermal energy requirements or sustained high power outputs for mobile applications. In these cases, hydrogen can serve as a low carbon substitute for fossil fuels. The UK Government updated its low carbon hydrogen production capacity in April 2022 from a 5GW target to 10GW by 2030, in a move that emphasises the government's commitment to integrating hydrogen technology into the UK economy. To truly realise the benefits of hydrogen as an energy vector, several milestones must be achieved: low carbon hydrogen must become competitive on price, and hydrogen supply must become accessible to consumers through effective distribution and storage.

The hydrogen value chain is the sum of all constituent parts which facilitate the use of hydrogen, encompassing all phases of production, storage, distribution, and consumption (markets). Figure 1 shows a non-exhaustive, condensed version of a hydrogen value chain, highlighting some of the key technologies which underpin the hydrogen sector.

[1] HW Government. UK becomes first major economy to pass net zero emissions law. GOV.UK. [Online] Department for Business, Energy & Industrial Strategy and The Rt Hon Chris Skidmore MP, 27 06 2019. [Cited: 18 04 2022.] https://www.gov.uk/government/news/uk-becomes-first-major-economy-to-pass-net-zero-emissions-law.





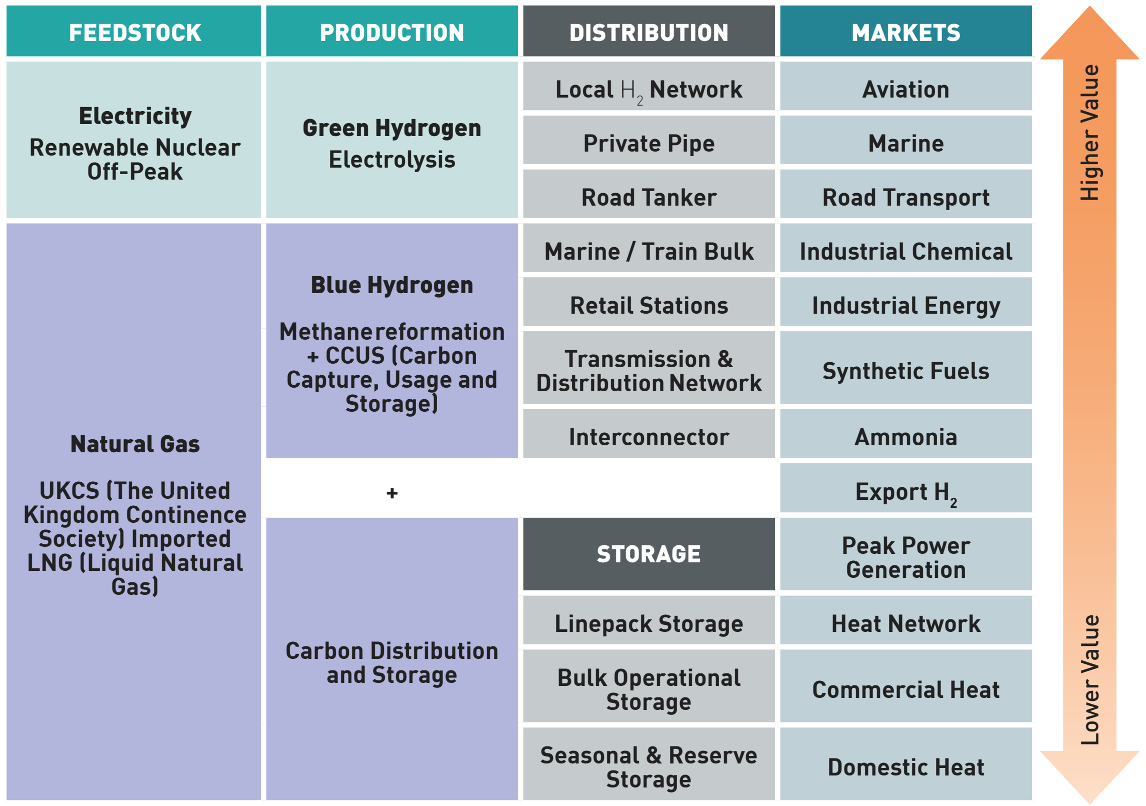



Figure 1: Condensed Hydrogen Value Chain [1].

The low 'readiness' of hydrogen supply chains is a nationally recognised barrier to adoption, and although a challenge to develop and upscale, doing so could provide a lucrative opportunity for UK manufacturers and suppliers alike. The primary aim of this paper is to discuss how the Midlands region can contribute toward green hydrogen production, which could be done by developing the supply chain of electrolysers. Hydrogen supply chains are still in the development phase, so for this reason evaluating whether the Midlands' industrial sectors could enter the electrolyser supply chain was a focal point of the discussion.

To evaluate whether the Midlands can contribute to the supply chain involved mapping each component for each sub-assembly of a containerised electrolyser. A workshop was carried out with an electrolyser technical expert and a group of MTC supply chain experts, who collectively gave their views on whether each sector could supply each component. This generated the information in Table 2 (page 8), showing each sector's ability to contribute to the electrolyser supply chain, with varying proficiency.

[1] Gowdy, Johnny. Regen Hydrogen Insight Paper. Regen - Transforming Energy. s.l. : Regen, 2020.

| PROFICIENCY | COLOUR |
|---|---|
| Experience not applicable to component | 0.00<br>0.25<br>0.50 |
| Expertise in the field, could pivot with significant investment | 0.75<br>1.00<br>1.25 |
| Supply component for a different application, could pivot with minimal investment | 1.50<br>1.75<br>2.00 |

Increasing Proficiency

Table 1: Numerical/coloured scale used to describe sectors' proficiency in electrolyser supply chain contribution.

| | Midlands' Industrial Capabilities | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Electrolyser Sub-Assemblies | Aerospace | Construction | Health Care | Automotive | Energy Sector | Defense | Food and Drink | Infrastructure | Chemical Industry | General Manufacturing |
| Water Purification Systems | 0.80 | 0.00 | 2.00 | 0.40 | 0.80 | 1.20 | 1.00 | 0.00 | 1.80 | 0.40 |
| Power Systems | 2.00 | 2.00 | 0.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fan Cooling System | 1.00 | 0.00 | 0.00 | 1.00 | 2.00 | 0.00 | 2.00 | 0.00 | 2.00 | 0.67 |
| Hydrogen Purification | 2.00 | 0.00 | 0.00 | 1.00 | 2.00 | 2.00 | 1.00 | 0.00 | 2.00 | 2.00 |
| Hydrogen Pipework | 1.50 | 1.00 | 2.00 | 2.00 | 1.50 | 1.50 | 2.00 | 1.00 | 2.00 | 1.00 |
| Hydrogen Generation | 1.33 | 0.00 | 1.33 | 1.33 | 1.33 | 2.00 | 0.33 | 0.00 | 1.33 | 1.33 |
| Shipping Containers | 0.00 | 2.00 | 0.00 | 0.00 | 0.00 | 2.00 | 0.00 | 0.00 | 2.00 | 2.00 |
| Container Gas Monitoring | 2.00 | 1.00 | 1.00 | 2.00 | 1.00 | 2.00 | 0.00 | 0.00 | 0.00 | 1.00 |
| Pump and Gas Separation Vessels | 0.33 | 0.67 | 0.67 | 1.33 | 1.67 | 0.33 | 1.00 | 0.67 | 2.00 | 2.00 |
| Ancillary Equipment | 2.00 | 2.00 | 0.00 | 0.00 | 2.00 | 2.00 | 2.00 | 0.00 | 2.00 | 0.00 |
| Total Sector Average | 1.30 | 0.87 | 0.70 | 1.11 | 1.43 | 1.50 | 0.93 | 0.17 | 1.51 | 1.04 |

Table 2: Proficiency of the Midlands' industrial sectors to provide componentry for each electrolyser sub-assembly, with proficiency defined as stated in Table 1.

The final section of this paper describes the importance of a holistic approach to hydrogen adoption and makes it clear that hydrogen supply is not feasible without effective storage, distribution, or markets for consumption. To establish a complete UK hydrogen value chain, technology needs to be developed across the value chain at the same rate, and will always be dependent on the weakest link in the chain.

Some key points from the paper include:

- Hydrogen is becoming a globally recognised energy vector to decarbonise hard-to-electrify sectors.
- To date, hydrogen demand is primarily concentrated in the industrial sector, namely chemical processing and ammonia manufacture.
- The UK Government is proposing a twin-track approach to hydrogen production, where green hydrogen will play a small role, between 10 and 20%, using assumptions based on data from the UK Hydrogen Strategy. The UK could increase this percentage using access to renewable electricity and leveraging the capabilities of industrial clusters.
- Green hydrogen is not dependent on fossil fuel feedstock energy and can be generated from renewable sources.
- The Midlands region has the industrial capabilities to contribute to the complete supply chain for a containerised electrolyser system. This includes the technology which generates green hydrogen, provided the correct support and coordination was given to businesses to develop their product portfolio.
- For the Midlands to realise this opportunity of increased electrolyser manufacture, a zoomed-out, holistic approach to the hydrogen value chain needs to be adopted, where industrial capabilities and research and technology organisations (RTOs) can support both delivery and consumption technologies.
- Hydrogen production and consumption are dependent on effective distribution and storage. Some key technologies are described and their applicability to hydrogen production is discussed.
- Hydrogen is being researched and developed for use in a range of applications including aviation, logistics, domestic heating and power. Hydrogen as a fuel is at a much lower technology readiness level (TRL) than hydrogen use in industry or hydrogen production technologies.
- Industrial sectors present a current opportunity to provide low carbon hydrogen, which comes primarily from ammonia manufacture and oil refineries. Iron/steel and industrial heating are also looking to incorporate hydrogen, presenting a significant opportunity, albeit at a lower TRL which would become more important in the future.

In the closing section, recommendations have been provided based on the findings of this paper.

## RECOMMENDATION 1 – GREEN HYDROGEN PRODUCTION

1. UK aim: Deliver green hydrogen at a competitive price. Carbon taxing will reduce the competitive advantage of GHG emitting hydrogen production. The UK has the capabilities (technical expertise) and resources (access to low-cost renewable energy) to increase green hydrogen production. The UK Government needs to establish knowledge and capability gaps, and devise plans to realise these opportunities. Doing so will prove significant for domestic and international trade as the world realises the potential of hydrogen.

2. Midlands objective: The Midlands region has the industrial capabilities to provide all components and expertise needed for a containerised electrolyser supply chain. Supporting the industry in this way will allow for increased UK electrolyser manufacturing capacity. A hydrogen supply chain is a critical foundation which a hydrogen economy will depend upon. Supply chains are fundamental to manufacturing, requiring action now, by providing businesses with the correct support and guidance in order to increase their maturity, as well as maximising the opportunities when they arise.

## RECOMMENDATION 2 – THE IMPORTANCE OF A HOLISTIC APPROACH

Industry leaders should work more closely with government to create both short-term and longterm plans and strategies for the industry. These should provide actionable statements formed from value chain analysis, considering the risks and opportunities previously identified. Government should look to support these proposals both financially and operationally, to enable the industry to build competitive advantage.

1. Re-use existing infrastructure where possible. Thermal energy is provided to around 80% of homes in the UK using natural gas (1), resulting in a complex pipe network that spans the entire UK. Substituting hydrogen for natural gas in the network is a difficult challenge for several reasons, mainly the large difference in density and the damage caused to pipework as a result of hydrogen embrittlement. Many gas companies are taking the initiative to substitute pipework with 'hydrogen ready' pipes in anticipation of adoption. Whether the pipe network is used for domestic heating or to cheaply deliver a hydrogen supply across the country, leveraging existing infrastructure is a financially beneficial solution.

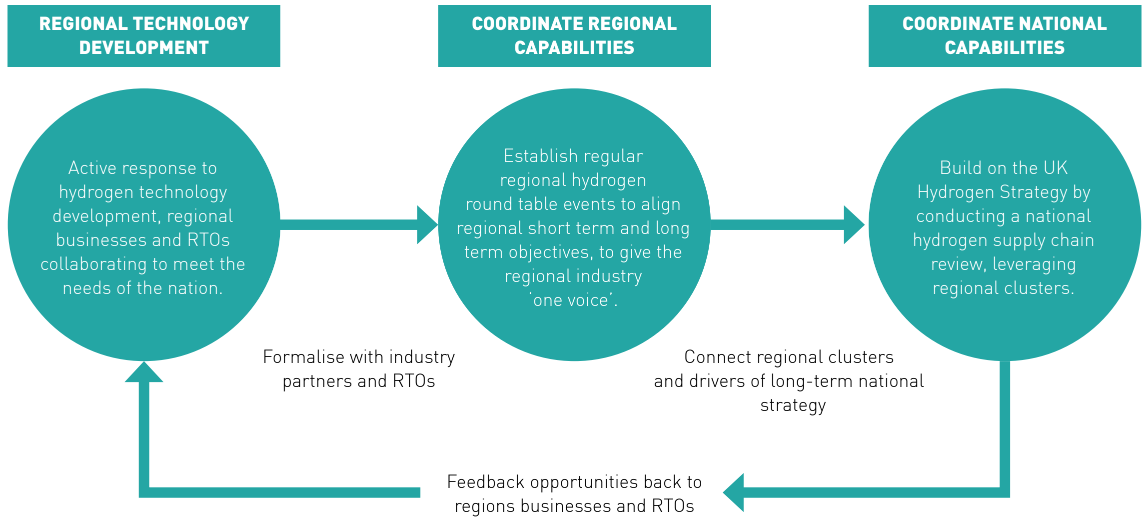
2. Decarbonise hydrogen production in the industrial sector. Industrial sectors consume hydrogen in the biggest quantities globally, and need low carbon hydrogen in high quantities now, in sectors such as ammonia manufacture and oil refineries. Decarbonising hydrogen production in these industries will replace grey hydrogen production and should be a priority. Using hydrogen as a fuel in applications such as transport could play a major role in future, but currently, the technology is at a low technology readiness level (TRL) and will not likely draw significant demand for some time.

[1] Roser, Hannah Ritchie and Max. Energy mix. Our World in Data. [Online] University of Oxford, 2020. [Cited: 24 03 2022.] https://ourworldindata.org/energy-mix#citation.





3. Coordinate and align both regional and national approaches to the production of a hydrogen value chain.




3.1 Active response to hydrogen technology development, regional businesses and RTOs collaborating to meet the needs of the nation. The government needs to provide continued support for first movers and work to address investment risk. This can be achieved by initially supporting cluster projects and pooling capital to allow the highest number of beneficiaries per investment. To support businesses, targeted loans, grants, and other tools can be used to provide the private sector with the resources that it needs to grow a market, distributing both risk and rewards. RTOs must provide businesses with tools to grow the market, where technology development is guided by regional short-term objectives and national long-term aims. Facilitate development by taking an active approach to hydrogen standards and regulation, where safety is prioritised while giving RTOs freedom to safely experiment.

3.2 Establish regular regional hydrogen round table events to align regional short term and long term objectives, to give the regional industry 'one voice'. Having a single entity to coordinate and develop the value chain initially by region, and then combined to form a national map, would help to inform decisions surrounding project placement and enable businesses to fully understand how their region's capabilities compare nationally. If this model was established for all UK industrial regions it would increase visibility and collective direction, providing Britain with a more efficient performance on a global scale.

3.3 Build on the UK Hydrogen Strategy by conducting a national hydrogen supply chain review, by combining regional clusters. The concept of the 'one voice' referred to in point 3.2 is now scaled up on a national level, where the voices of each industrial cluster can be combined nationally to form a complete UK landscape of capabilities and resources. This approach facilitates transparency, allows regions to communicate with the government directly, and allows for short term objectives to be completed by each regional area which aligns with the UK's long term aim.





# INTRODUCTION

### UK COMMITMENT TO NET-ZERO

Some of the biggest questions for our government today are concerning increased energy demand and climate change, which have both resulted in social and economic damage across the world. More than 80% of the world's energy comes from fossil fuels, and to reduce dependence on non-renewable energy, there needs to be a drive for sustainable and low-carbon solutions [1]. Decarbonisation of all sectors is needed to honour the 2016 Paris Agreement, limiting global warming to under 2°C. Putting the UK's pledge of net-zero emissions by 2050 into law was one of the first major steps towards this goal; an ambitious but achievable target. Net-zero can be delivered if the UK looks to lower net energy consumption, switches to low/zero-carbon energy carriers, promotes renewable energy production and accelerates the development of carbon capture, utilisation, and storage.

The "Ten Point Plan for a Green Industrial Revolution" was the UK Government's initial road map to address climate change, with a focus on reducing emissions across the economy. Hydrogen as an energy carrier was considered one of the ten points, and over the last two years has gained momentum as a catalyst for a net-zero future. The Ten Point Plan emphasised the role of a hydrogen economy in the UK, using hydrogen technology as a flexible alternative energy source for power, heating, transport, and industrial applications.

The UK Hydrogen Strategy was released in August 2021, which gave greater clarity about the government's approach to hydrogen technology. It began to highlight the business case for hydrogen and its role across multiple sectors, emphasising that financial support will be provided to stimulate adoption. The strategy highlighted significant commercial opportunities, and most notably pledged a UK target of 5GW low carbon hydrogen production by 2030, which could provide over 9,000 jobs nationwide [2]. A £240 million Net Zero Hydrogen Fund will provide financial support for the commercial development of low-carbon hydrogen projects [2].

The Levelling Up White Paper was released in February 2022, and ties together many of the preceding documents released by the government regarding the green industrial revolution. The new policy regime set out for 'levelling up' offered a post-Covid plan to boost social and economic value in the UK, and crucially focuses on driving innovation to support low carbon solutions through financial incentives. In the document, the UK Government pledged a £100 million investment target to be distributed between three innovation accelerators of research and development in energy technology, like those in Silicon Valley in the US, with one of the centres being built in the West Midlands [3]. A total of £26 billion investment has been allocated for a green industrial revolution, to support the transition to net-zero [3]. Hydrogen has a clear role in this plan and will need financial stimuli like this to provide technological development and infrastructure to support it.

[1] Roser, Hannah Ritchie and Max. Energy mix. Our World in Data. [Online] University of Oxford, 2020. [Cited: 24 03 2022.] https://ourworldindata.org/energy-mix#citation.

[2] HM Government. UK Hydrogen Strategy. Business, Energy & Industrial Strategy. London : s.n., 2021.

[3] Leveling up the United Kingdom. London : s.n., 2022.

The British Energy Security Strategy was released in April 2022 and builds on the energy-related focal points presented in the Levelling Up White Paper, including energy control, lowering emissions, and increasing affordability of energy in the UK in light of recent price volatility. The policy paper pledges to double the initial hydrogen production capacity target to 10GW by 2030, indicating a more aggressive drive toward hydrogen technology [1]. In addition, by 2025 the government plans to: set a new business model for hydrogen distribution and storage, in addition to setting a level playing field for hydrogen certification, which will demonstrate high-quality hydrogen from both British suppliers and imports.

UK Government then put forward a Hydrogen Sector Development Action Plan in July 2022, which began to set out a roadmap for how the above pledges could be delivered. The report is split into 5 chapters focusing on Investment, Supply chains, Jobs & Skills, Exports and finally a section on Monitoring & Evaluating, with the combination of these chapters to encapsulate the 'holistic' approach to delivering a hydrogen economy. The purpose of the report is to highlight and characterise opportunities in these key chapters, in addition to describing the actions being taken by government to realise and maximise the rewards from up-scaling engagement with hydrogen technology in the UK.

Although hydrogen is attracting a great deal of attention currently, it is not a silver bullet to the world's energy crisis; it does however provide a means to moving away from the continued dependence on fossil fuels and could soon become a part of everyday life when combined with other low carbon strategies. Manufacturing and technology companies will be in the driver's seat for this transition, being directed by the government and the needs of society. This is not the only solution for net-zero, and should be thought of as a complementary partner to electrification and other low-carbon technologies.

## HYDROGEN'S ROLE IN NET-ZERO

Although hydrogen use seems to be a new idea, the truth is that people have been using hydrogen consuming technologies for centuries, with some of the first hydrogen bubbles generated in electrochemical processes back in the 1800s. Since then, hydrogen has been used in combustion engines, fertilizer production, airships and most impressively, put humanity into orbit in the 1960s [2]. Hydrogen is a difficult gas to deal with due to its reactivity, making containment and distribution a challenging endeavour. In addition, manufacture of hydrogen has characteristically been a polluting process, and only now is it deemed acceptable with the advent of 'net-zero emissions' and not 'zero-emissions'. Major advancements have occurred over the last decade, which have resulted in an international reconsideration of hydrogen use, as a means to reduce fossil fuel consumption.

The UK Government is looking to hydrogen as a bridge toward net-zero and is providing policy incentives to ensure the economy has the support needed to stimulate widespread adoption of hydrogen technology. Hard-to-electrify sectors are a focus, and typically refer to applications of high power outputs for long periods of time, making electrification unsustainable. This is primarily due to the size of the battery needed to deliver the sustained high power output in transport, and the high thermal energy needed for industrial heat applications. Some examples include aviation, heavy goods vehicles, and industrial processing, which are among the most energy-intensive sectors and typically rely on the combustion of fossil fuels for thermal energy. Hydrogen therefore could support these sectors as an alternative energy carrier to reduce dependence on electrification.

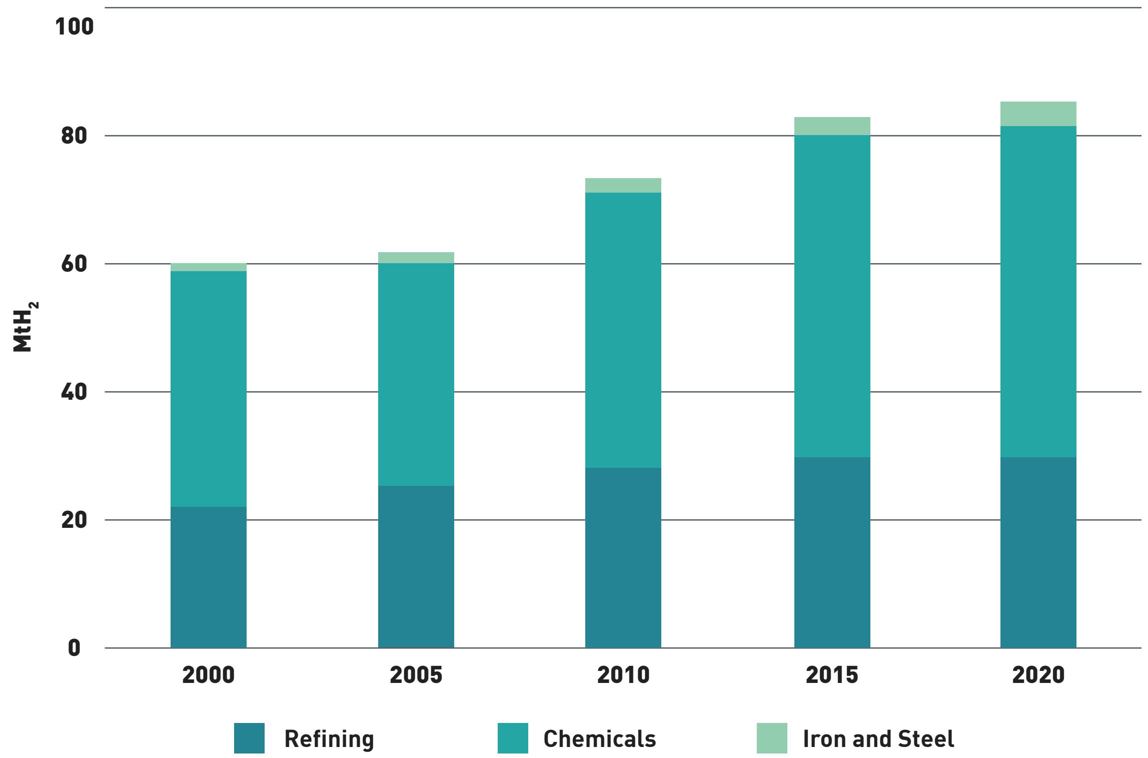
Hydrogen demand is predominantly concentrated in industrial sectors, manufactured from natural gas without carbon capture, and consumed in chemical or refinery operations. Figure 2 shows the global hydrogen demand between the years 2000 and 2020.

[1] British energy security strategy. 2022.

[2] International Energy Agency. The Future of Hydrogen - Seizing today's opportunities. Japan : IEA for the G20, 2019.








Oil refineries typically 'crack' longer, more dense hydrocarbon chains to form shorter more useable compounds, reducing density and increasing combustibility.

The chemical industry's demand is dominated by ammonia production for fertilisers, where hydrogen is joined with nitrogen in the Harber-Bosch process.

Iron and steel industries where hydrogen is used as a reducing agent, as opposed to 'coke' which is derived from coal, in a less carbon-intensive process.

Figure 2: Graph of hydrogen demand by sector between 2000 and 2020 [1].

*Note: "Others" refers to small volumes of demand in industrial applications, transport, grid injection and electricity genertation. $MtH_2$ means Megatonne, abbreviated as Mt, is a metric unit equivalent to 1 million (106) tonnes, or 1 billion (109) kilograms.*

*Source: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Megatonne_(Mt)#:~:text=Megatonne%2C%20abbreviated%20as%20Mt%2C%20is,billion%20(109)%20kilograms.*

[1] Global Hydrogen Review 2021. Paris : IEA. 

Due to the high volume of consumption in these sectors, and the lack of a hydrogen infrastructure globally, the most economic supply model is production on-site, meaning they operate independently of an external hydrogen supply. Decentralised production is common in these industries due to both the economic benefits of mass production, and the reduced distance between production and consumption. Production in this way could incentivise smaller companies to meet regional demand, which may help reduce the strain felt by large up-scaling of hydrogen infrastructure and supply chains.

The source of energy has a large effect on whether it can be deemed 'clean' or not. For example, an electric car running from electricity generated in a coal power plant is not beneficial for the environment; in a similar way that hydrogen generated from fossil fuels without carbon capture will be of no environmental utility. As of 2018, the UK produced between 10-27TWh of hydrogen annually according to the Committee of Climate Change (CCC) [1], with only 4% generated from renewable energy, the rest using fossil fuels.

Figure 3 shows the hydrogen production by source globally as of 2020, and then the predicted quantities for 2025 and 2030 from the International Energy Association (IEA), in line with the net-zero global emissions by 2050 scenario.

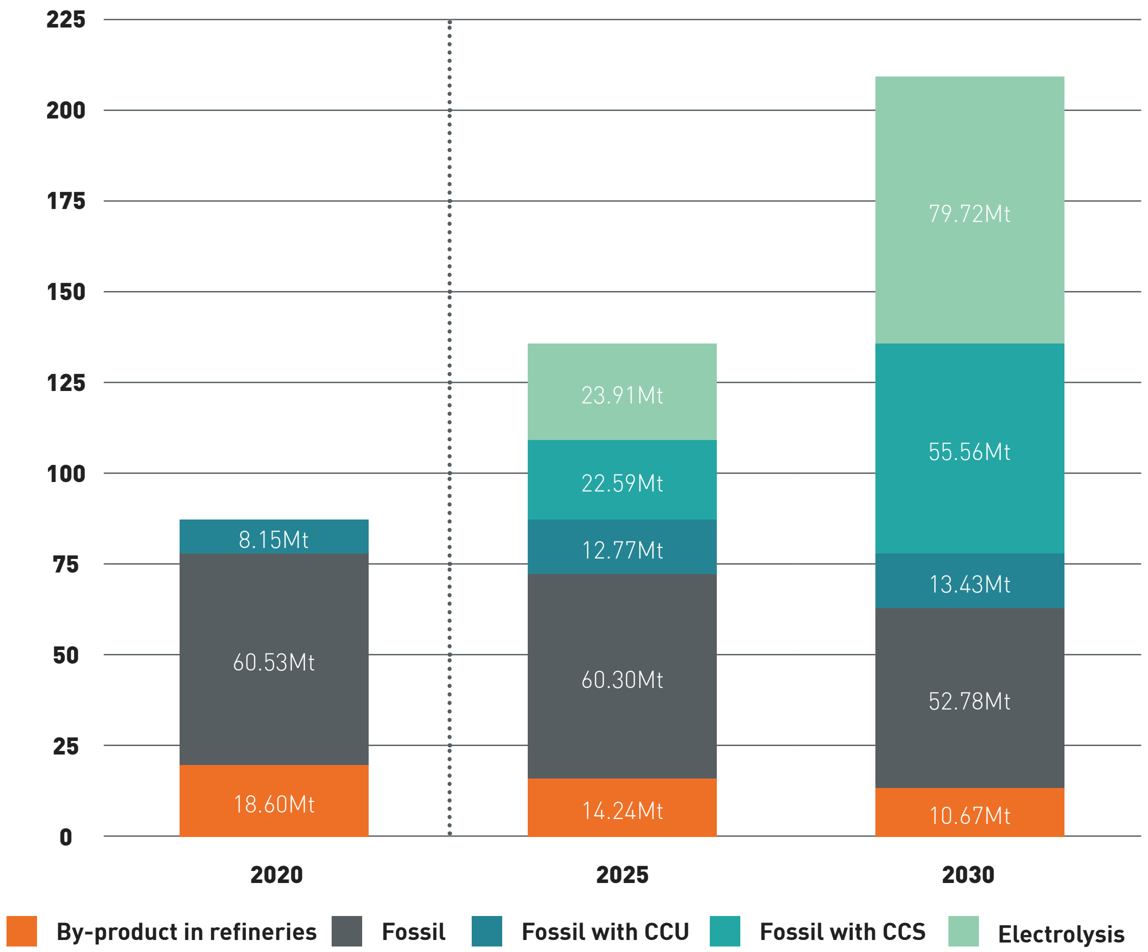



Figure 3: Global hydrogen production percentage by source in 2020 and the predicted production in 2025 and 2030, based upon the IEA Net Zero Emission (NZE) by 2050 scenario [1].

*Note: $MtH_2$ means Megatonne, abbreviated as Mt, is a metric unit equivalent to 1 million (106) tonnes, or 1 billion (109) kilograms.*

Source: *https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Megatonne_(Mt)#:~:text=Megatonne%2C%20abbreviated%20as%20Mt%2C%20is,billion%20(109)%20kilograms.*

[1] Committee on Climate Change. Hydrogen in a low-carbon economy. 2018.

[1] International Energy Agency. Hydrogen. [Online] 11 2021. [Cited: 22 03 2022.] https://www.iea.org/reports/hydrogen.

As of 2020, ~0.56% of hydrogen was produced by electrolysis (a value so small it cannot be seen on the graph), the rest using fossil fuels, where only ~9% of hydrogen was produced with carbon capture and utilisation. The remaining ~90% of production released all exhaust gases into the atmosphere. The 2025 and 2030 data sets are based upon assumptions that deliver net-zero emission by 2050, a good indicator of how the IEA envisions hydrogen production must change. 2030 is predicted to see a sharp increase in electrolyser use, forming the biggest hydrogen production by percentage, where 38% of the total demand is met by electrolytic production. Electrolysers can generate hydrogen using renewable electricity, do not use fossil fuels, and do not emit any greenhouse gases. This being said, fossil fuels are still expected to form a considerable portion of production. However, the addition of 'carbon capture and utilisation' (CCU) and 'carbon capture and storage' (CCS), enables the process to be net-zero-emitting.

To meet the UK Government's 2030 target of reducing emissions by 78% (when compared to 1990s emissions) action needs to happen now, and the Midlands manufacturing community has an opportunity to play a critical role in the UK's global impact [1]. The Midlands Engine published its Hydrogen Technologies Strategy in December 2021, which showcases the phenomenal expertise contained within the region and highlights the role hydrogen will play in delivering it's Green Growth plan. The Midlands Engine took the initiative to translate the government publications into an industry-led 'Ten Point Plan for Green Growth', containing a specific Hydrogen Technologies Strategy which aligns the national needs with the capabilities of the Midlands [2].

Integration of hydrogen into the economy will affect all sectors, as energy is involved in almost every industry. For a hydrogen economy to be operational at scale, two key components must be in place before consumption can occur;
low cost/carbon hydrogen production and effective distribution to consumers. If a hydrogen pipe network were to be introduced this could greatly reduce the issues associated with hydrogen transport and facilitate a timelier integration with the economy. But, producing a hydrogen network is not viable without several large-scale low carbon hydrogen production sites, which are unlikely to be commissioned due to the current low demand for hydrogen. This is caused in part by the lack of a national supply network, which is partly due to a lack of production capacity. This loop can be thought of as the 'chicken and the egg' hydrogen problem, where resistance is felt by producers, distributors and consumers, who do not want to be the ones to take a risk and produce a commodity without a demand, in anticipation of the future.

The Manufacturing Technology Centre (MTC) pioneers efforts to bridge the 'valley of death', typically referred to as the disconnect between academia and industry. It broadly refers to the risk associated with integrating innovative technology into a long-standing industrial process, where the risk comes as a consequence of the uncertainty relating to the low technology readiness (TRL).

[1] Global Hydrogen Review 2021. Paris : IEA. All rights reserved, 2021.

[2] Midlands Engine. Ten Point Plan for Green Growth in the Midlands Engine. 2021.





Although hydrogen technology is not currently ready for mass deployment and use, supply chains needed for the transition can be identified now and supported to promote British manufacturing and incentivise the reshoring of supply chains. Several market opportunities and supply chain gaps exist currently across the hydrogen value chain in the UK, as discussed in a report from Business, Energy, and Industrial Strategy (BEIS), released in June 2022, titled Supply Chains to Support a Hydrogen Economy. The report analyses supply chain requirements for hydrogen production, transmission and distribution/storage, delivering a comprehensive overview of the current UK hydrogen supply chain. Where gaps and market opportunities were identified it's critical that national action takes place, failing to do so would force increased imports and outsourcing of the opportunity to overseas companies, increasing their comparative expertise and forfeiting the potential benefits.

A similar scenario occurred when offshore wind energy was added to the UK energy mix in a meaningful way, where the need for renewable energy outweighed the need to promote UK manufacturing. This led to demand being met by European imports, supporting businesses that were early adopters that met demand as soon as it arose. The need for renewable energy only grew, and due to the experience of the predominantly Danish and German suppliers, they quickly became world leaders in renewable wind energy technology. The IPRC publication titled, 'A Review of how the Midlands can enter the Offshore Wind Supply Chain' addressed how the Midlands region could make use of manufacturing expertise within the region to support national supply chain gaps, giving recommendations on how to do so.

## HYDROGEN VALUE CHAIN

The hydrogen value chain is defined as the complete set of business activities needed to operate a hydrogen economy, encompassing all phases of production, storage, distribution, and consumption. Figure 4 shows a non-exhaustive summary of the hydrogen value chain, highlighting the leading production methods, delivery options, markets, and some competitive hydrogen production technologies out of line with the 'twin-track' UK Government approach, all ranked by cost in ascending order.

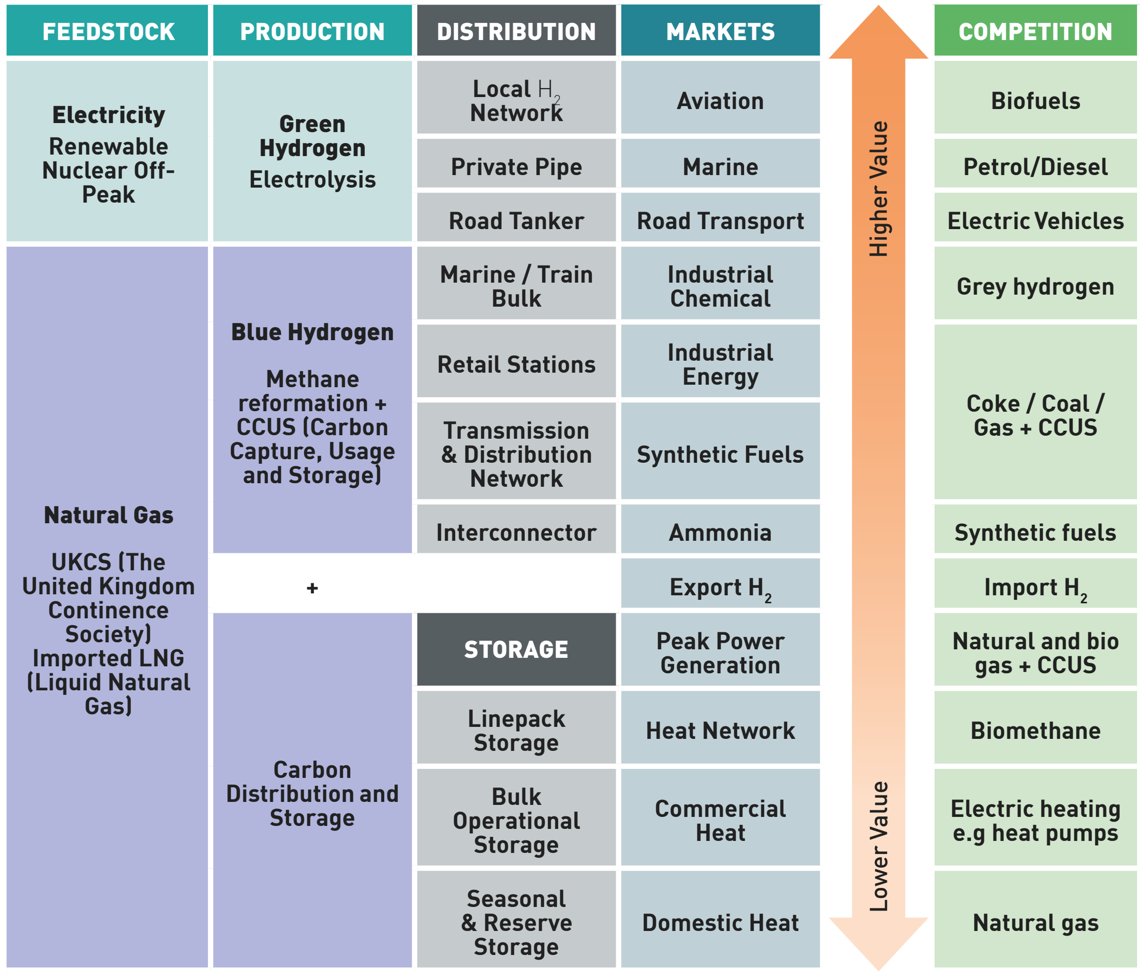



Figure 4: Condensed Hydrogen Value Chain [1].

[1] Gowdy, Johnny. Regen Hydrogen Insight Paper. Regen - Transforming Energy. s.l. : Regen, 2020.





Hydrogen production is better considered as energy conversion, where a 'feedstock energy' undergoes a process to convert that energy (electricity or natural gas) into hydrogen. Hydrogen is sometimes referred to as an 'energy vector' as it can be made from electricity, and then converted back, or burned as a fuel, therefore acting as an energy carrier or vector. There are several different ways to generate hydrogen, however, the UK Government is supporting a 'twin-track' approach that will focus primarily on producing blue and green hydrogen. For blue hydrogen, the feedstock energy is natural gas, which undergoes steam methane reforming (SMR) with carbon capture, utilisation and storage (CCUS). Without CCUS, SMR generates grey hydrogen, which is the primary hydrogen source in the UK to date. For green hydrogen, water undergoes an electrochemical process where renewable electricity is the input/feedstock energy. Each technology is illustrated under the headings 'Feedstock' and 'Production' on the left of Figure 4, with some competing fuels sources of production shown on the right in green.

Hydrogen can either be transported directly to its consumer or stored to meet demand when it arises. Some examples of key storage and distribution methods are shown in grey in Figure 4, where bulk storage methodologies attain economies of scale and therefore result in a unit storage price lower than smaller-scale facilities such as pressure vessel containers. Hydrogen is the lightest element in the periodic table, meaning that hydrogen can permeate through both the containment material and the component joints or welds, which results in a much higher degree of mitigation to prevent leakages. Additionally, special consideration must be given to the choice of materials used in hydrogen applications, as a phenomenon known as hydrogen embrittlement can occur in hydrogen environments, which can degrade material properties.

Several markets form a consumer base, some of which are highlighted in the 'Markets' column in Figure 4, ranked by price in ascending order starting from the bottom. This report addresses only some of the markets within a hydrogen value chain, and focuses on the markets that present the clearest opportunity for the Midlands region. With a hydrogen economy affecting almost all sectors, the opportunities for supply chains to support integration into society are great. The Midlands region has expertise across several sectors that will certainly have a role to play in a thriving hydrogen economy. Identifying those opportunities is the important first step in realising that potential.





## LOW-CARBON HYDROGEN PRODUCTION

The UK Government's most recent pledge set a target of 10GW low carbon production capacity by 2030, which will require a steep increase in low carbon hydrogen production and highlights a significant opportunity for businesses across the UK. Figure 5 shows the 'Proposed UK Electrolytic and Carbon Capture, Utilisation and Storage (CCUS)-enabled Hydrogen Production Projects', as stated in the UK Hydrogen Strategy. When this strategy was released, it was the first national review completed for hydrogen technology, and this schematic encompasses all of the known hydrogen projects in the pipeline for production at the time of writing.

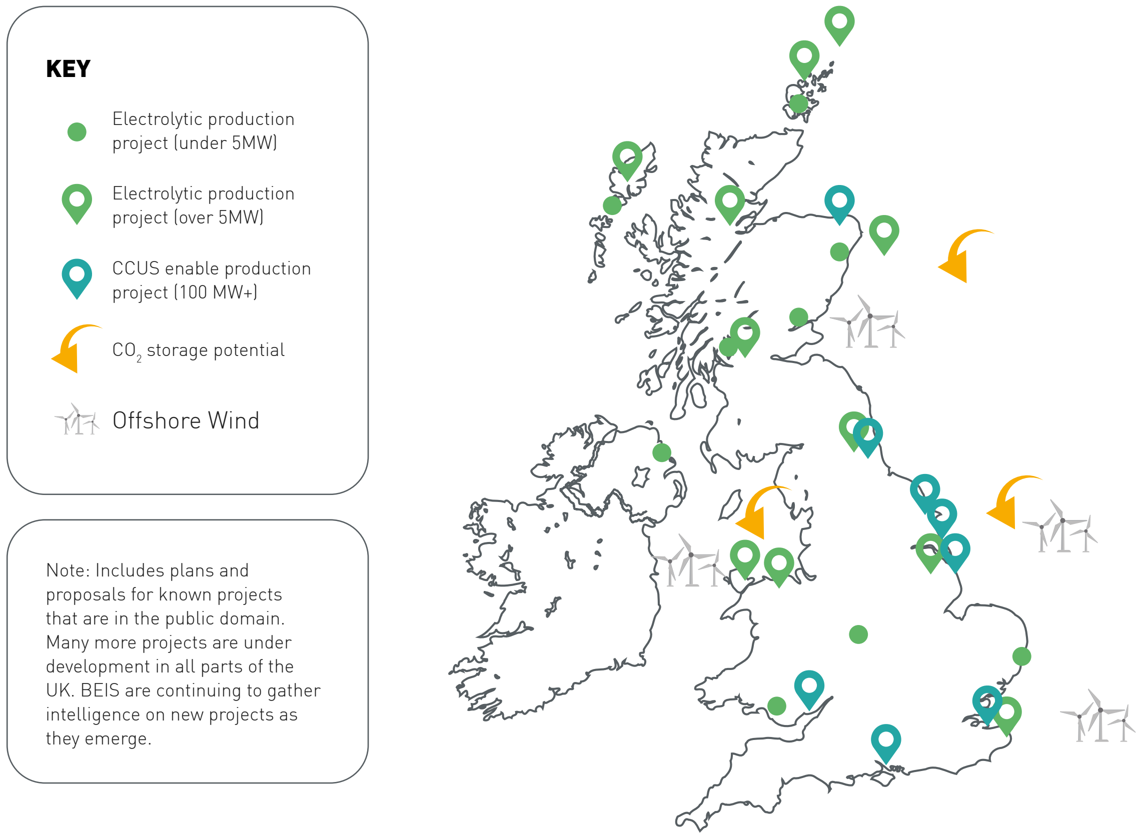



Figure 5: Proposed UK electrolytic and CCUS-enabled hydrogen production projects as of August 2021 [1].

[1] HM Government. UK Hydrogen Strategy. Business, Energy & Industrial Strategy. London : s.n., 2021.

### STEAM METHANE REFORMING (SMR) WITH CARBON CAPTURE, UTILISATION AND STORAGE (CCUS) – BLUE HYDROGEN

Blue hydrogen is the most accessible, as it's generally the cheapest low-carbon hydrogen production method, in addition to being the best-understood technology. To give some context, approximately 80% of the world's hydrogen is manufactured using gas reforming and coal gasification, both highly polluting processes made from non-renewable sources [1], generating grey and black hydrogen respectively. The possibility of retrofitting carbon capture technology to existing grey hydrogen facilities is also a very appealing prospect as it essentially keeps these facilities in the business. $CO_2$ post-processing is still in its infancy, and currently net increases energy consumption of grey hydrogen facilities, therefore without a steep carbon tax, companies have little incentive to decarbonise. Extracting $CO_2$ from flue gases for use in other sectors is still costly, and mass transportation and storage of flue gases rely heavily on geological sequestration, which is dependent on location.

Blue hydrogen is best suited to locations that contain carbon management systems and storage, as pre-combustion carbon capture (used in blue hydrogen production) generates large amounts of carbon-containing waste which must be safely disposed of. The rate at which blue hydrogen can be manufactured will be dependent on the CCUS technology and is, therefore, an area of focus to develop over the coming years to ensure the target of reaching net-zero by 2050. Because of the investment required for such a system, the government favours 'industrial clusters' where the benefits of the infrastructure can be experienced by multiple companies. Examples of hydrogen industrial clusters are HyNet Northwest and the East Coast Cluster, which will facilitate and lead hydrogen integration into society.

Using CCUS to decarbonise existing hydrogen production is an important step toward decarbonisation, and blue hydrogen will be important in generating a supply that can then be distributed and consumed. As a percentage of the total hydrogen project capacity, 80-90% blue hydrogen is very high and is dependent on natural gas. To balance the supply, electrolyser capacity could be increased simply by leveraging the capabilities of the UK, for which the Midlands will play an essential role.

[1] HM Government. UK Hydrogen Strategy. Business, Energy & Industrial Strategy. London : s.n., 2021.





### ELECTROLYTIC HYDROGEN PRODUCTION – GREEN HYDROGEN

One of the biggest pre-conditions for low-cost green hydrogen is low-cost energy. This typically comes from surplus wind electricity, where production is intermittent and generates energy in times of low demand and therefore low cost. Green hydrogen technology is still in its infancy and although the unit price is beginning to decrease, is still the more expensive option than blue hydrogen in most cases. The UK is a global leader in offshore wind energy [1], which is one of the best sources of cheap low carbon electricity. The UK is also home to one of the biggest electrolyser manufacturers in the world in ITM Power, highlighting a supply of both the expertise and resources to increase sustainable hydrogen production using electrolysers.

The process could be supported by a near completely UK supply chain, but only if the development of such supply chains begins now.

When a direct electric current is applied to water, it can dissociate the constituent elements, producing both hydrogen and oxygen gas. The hydrogen obtained in this process has a purity that can reach 99.999% once the hydrogen has been dried and purified. An electrolytic reaction broadly requires an anode and cathode separated within an electrolyte, where the material of the electrolyte distinguishes the type of reaction. There are three common types of electrolyser systems whose differences are attributed to their electrolyte material. These are summarised in the table below, namely alkaline electrolysers, polymer electrolyte membrane (PEM) and solid oxide electrolysers (SOE).

| | Type of electrolyser | | |
|---|---|---|---|
| | **Alkaline** | **PEM** | **SOE** |
| **Development status** | Commercial | Commercial, small and medium-scale application (←300 kW) | Undergoing research |
| **Brief description** | Transport of hydroxide ion through electrolyte<br><br>Hydrogen generated at cathode<br><br>A liquid alkaline solution of sodium or potassium hydroxide used as electrolyte | Water reacts at the anode to form oxygen and hydrogen ions (protons)<br><br>Electrons flow through an external circuit and hydrogen ions selectively move across the PEM to the cathode<br><br>Electrolyte is a solid speciality plastic manual | Water at the cathode combines with electrons from the external circuit to form hydrogen gas and negatively charged oxygen ions<br><br>The oxygen ions pass through the solid ceramic membrane and react at the anode to form oxygen gas and generate electrons for the external circuit<br><br>A solid ceramic material used as the electrolyte |
| **Operating temperature** | 100-150°C | 50-90°C | 700-800°C |

Table 3: Types of electrolyser design [2].

[1] UK Research and Innovation. Harnessing offshore wind. UK Research and Innovation. [Online] 06 2021. [Cited: 15 04 2022.] https://www.ukri.org/news-and-events/responding-to-climate-change/topical-stories/harnessing-offshore-wind/#:~:text=The%20UK%20is%20presently%20the,10%25%20of%20the%20UK's%20power..

[2] International Renewable Energy Agency. Renewable Power-To-HydrogenI innovation. 2019.

Irrespective of the method of electrolysis, the general process can be characterised as shown in Figure 6. Starting from water, undergoing purification followed by the reaction in the hydrogen generation unit, to then be compressed and stored.

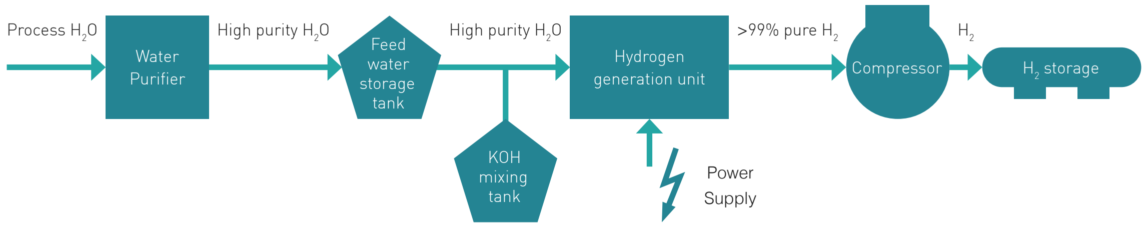



Figure 6: Process flow diagram of electrolytic hydrogen production [1].

Proton exchange membrane or polymer electrolyte membrane electrolyser (PEM) are the most compact and effective in coping with dynamic load balancing associated with utilising surplus intermittent renewable supply [1]. PEM electrolysers are less understood than alkaline electrolysers and have a higher capital expenditure (CAPEX) per unit. Most industrial applications use alkaline electrolysis due to its comparatively lower cost, operating temperature/pressure, and higher reliability. However, it is widely accepted by industrial specialists that PEM electrolysers are the future, due to their compact design and ability to increase plant production capacity for a given volume [1]. ITM manufactures PEM electrolysers and is one of many industry experts that support the technology.

A PEM electrolyser contains an electrolyte comprised of a solid polymer material that sits between the anode and cathode consists of and typically operates at around 70-90°C. Figure 7 shows a flow diagram of the electrolytic process.

[1] Robles, J O, Almaraz, S DL and Azzaro-Pantel, C. Hydrogen Supply Chain - Design,Development and Operation / Chapter 2 - Hydrogen Supply Chain Design: Key Technological Components and Sustainable Assessment. s.l. : Elsevier Ltd., 2018. 978-0-12-811197-0.





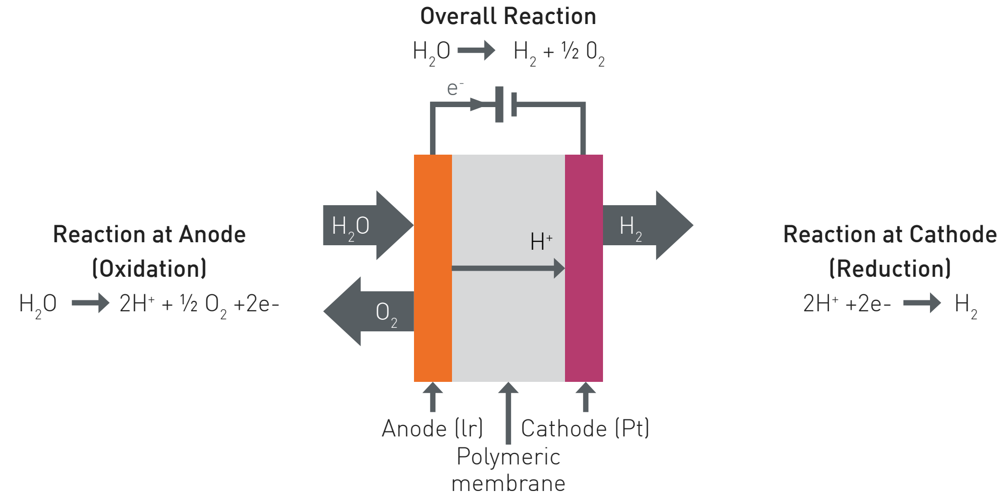



Figure 7: Electrochemical reaction in a polymer electrolyte membrane (PEM) electrolyser [1].

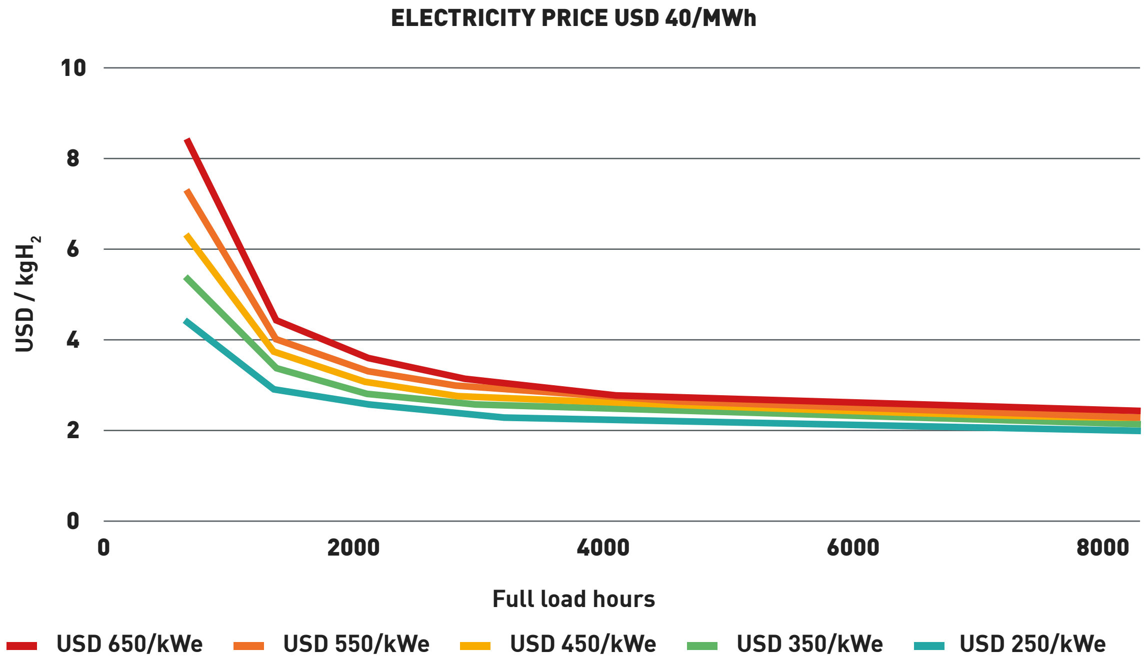
When a water molecule is incident on the anode, it splits into oxygen gas ($O_2$) and positively charged hydrogen ions (H+). During the separation, two electrons (e-) are released, which flow through the circuit as shown. This generates a net positive charge at the cathode which then draws the H+ ions towards it. Two protons (H+ ions) join with two electrons (e-) to then form hydrogen ($H_2$) as an output.

Several factors contribute to the production cost of hydrogen using this technology, including CAPEX, electricity costs, water to hydrogen conversion efficiency and operational hours (2). The CAPEX for electrolysis includes the hydrogen generation unit (the stack), the balance of plant required to operate the system, the construction of the system and the electricity grid connection.

To understand the levelised cost of a PEM electrolyser system, it is important to consider how the initial investment (CAPEX) and operational costs are distributed relative to the output price of hydrogen over a unit's lifetime, which is typically how competing hydrogen production methodologies are compared. The IEA has modelled two scenarios for hydrogen production as seen in Figure 8 (page 28), showing how the CAPEX cost and electricity cost affect the output price of hydrogen, and therefore the levelised cost of the system. Both graphs display the price of hydrogen per kg on the y-axis, and the number of operational hours on the x-axis, with the electricity price and CAPEX of the systems used as the control variables in this exercise.

[1] UK Research and Innovation. Harnessing offshore wind. UK Research and Innovation. [Online] 06 2021. [Cited: 15 04 2022.] https://www.ukri.org/news-and-events/responding-to-climate-change/topical-stories/harnessing-offshore-wind/#:~:text=The%20UK%20is%20presently%20the,10%25%20of%20the%20UK's%20power.

[2] International Energy Agency. The Future of Hydrogen - Seizing today's opportunities. Japan : IEA for the G20, 2019.



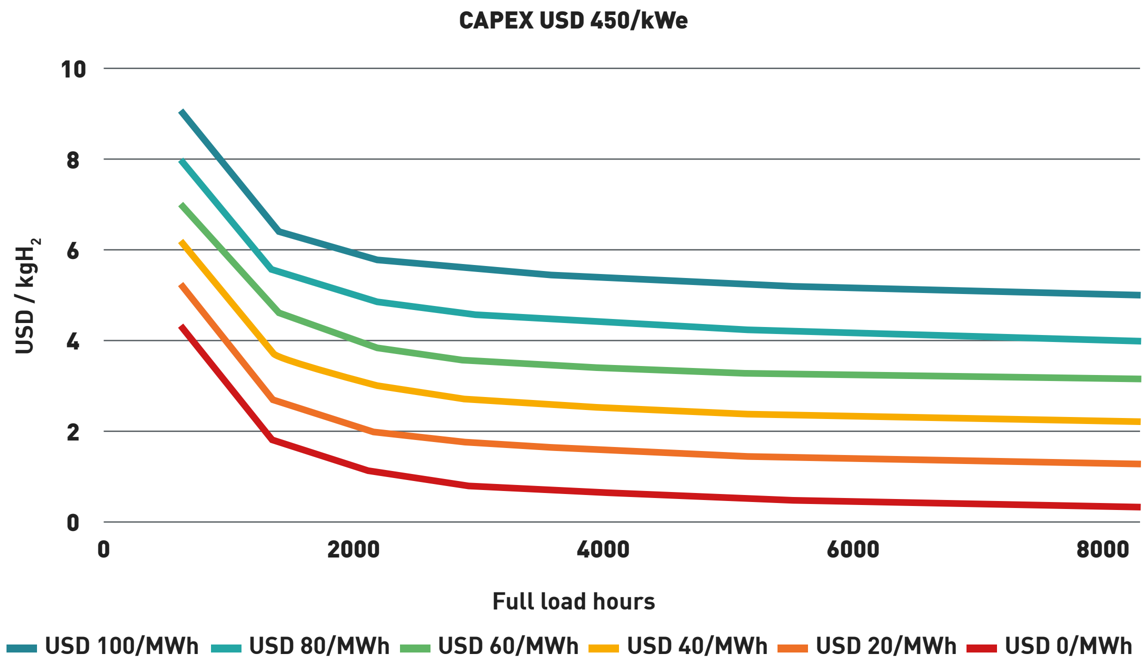




Figure 8: Levelised cost of hydrogen modelled for different electrolyser investment costs (top) and electricity price (bottom) [1].

[1] International Energy Agency. The Future of Hydrogen - Seizing today's opportunities. Japan : IEA for the G20, 2019.





In the first graph, the input electricity price has been fixed at $40 per MWh, and each line corresponds to a different CAPEX, which ranges from $250/kWe to $650/kWe. The initial hydrogen price is high, as typically the installation and commissioning of new sites are costly, but then over time decreases as operational hours increase, where the effect of CAPEX on the output price of hydrogen decreases and converges around a common value. The levelised cost is therefore similar for all system CAPEX values over an operational period based upon the assumptions in the example, identifying that for a constant electricity price, the cost of hydrogen investment does not have a large effect on the levelised cost over the system's lifetime.

The second graph in Figure 8 uses a fixed investment cost of $450 per kWe with varying energy prices. Each line on the graph denotes a range of prices between $0 per MWh and up to $100 per MWh. In this case, the output price of hydrogen per kg for each electricity price line does not converge at a point even after 8000 hours of operational time, indicating that the price of electricity has a strong effect on the output price of hydrogen.

To capitalise on hydrogen price, electrolysers can be used in conjunction with a renewable electricity supply, as an inter-seasonal energy storage mechanism to compliment the intermittency of renewables. The idea is to utilise surplus energy throughout the year as hydrogen for long term storage and sale, or to be used as needed on site. Any electricity can be used to conduct electrolysis, for example energy from the grid, but it is costly, and the electricity would be better suited for direct use by the consumer. In green hydrogen, renewable energy contributes between 50 and 90% of the total production costs, dependent on energy cost and the number of full-load hours that the supply can deliver [1].

Although blue hydrogen typically yields a lower cost per unit of hydrogen than an electrolyser, it does, however, fall victim to volatile gas prices. A sizable portion of the gas supply comes from overseas, decreasing the independence and control of external factors affecting the UK energy mix. Re-shoring energy production and systems could be important in the future as gas prices continue to rise and show volatile price action. If the production of green hydrogen was increased, it would facilitate a greater amount of control over production and mitigate the increase, which would be seen in the case of a nearly 90% dependence on natural gas for hydrogen. The IEA has recently released 'A 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas', which presents ten practical means to reduce natural gas dependence internationally, in light of the recent Russian invasion of Ukraine. The UK is one of the countries which is dependent on Russia for natural gas, among other European countries, and in future would greatly benefit from increased energy independence.

The levelised cost of fossil fuel consuming hydrogen production is also forecast to increase in line with net-zero targets, incentivising the use of electrolysers. Figure 9 (page 30) is an IEA prediction of the change in levelised cost of the leading hydrogen production technologies.

[1] Global Hydrogen Review 2021. Paris : IEA. All rights reserved, 2021.

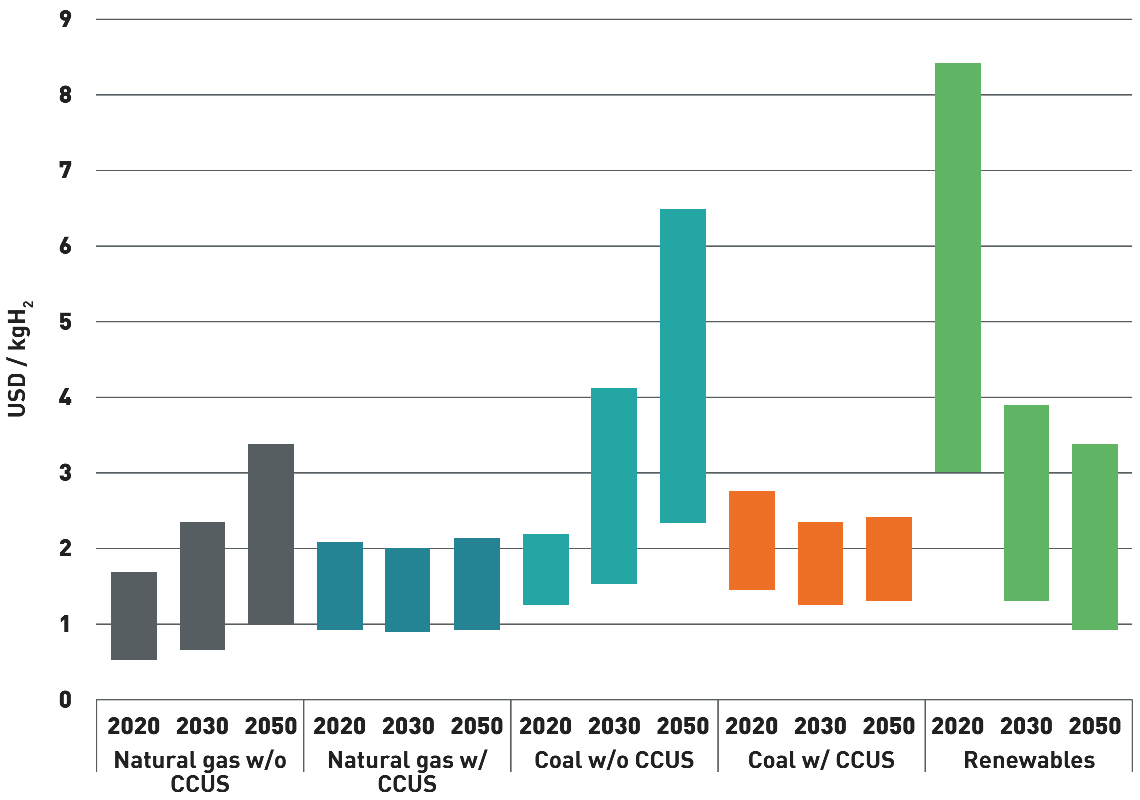



Figure 9: How the levelised cost of hydrogen will change from 2020 to the Net-zero emissions scenario as predicted by the IEA for 2030 and 2050 [1].

The fossil fuel burning technologies without carbon capture show a cost increase over time which is attributed to the global carbon tax designed to make these processes uncompetitive from an economical point of view. Fossil fuel burning technologies with carbon capture are forecast to stay largely the same, as high capture rates of 90-95% allow these processes into the window of net-zero Electrolysers are predicted to see a sharp decrease in cost over time, as the output cost of hydrogen for the technology is still very high when compared to SMR with CCUS. This cost will be reduced by heavily subsidising electrolyser development, up-scaling electrolyser manufacture and working to reduce the unit cost of electricity.

[1] Committee on Climate Change. Hydrogen in a low-carbon economy. 2018.





## ELECTROLYSERS IN THE UK

With electrolyser technology becoming more and more widespread, many companies are looking to enter the market, with the current pipeline for UK green hydrogen projects standing at approximately 484MW in production capacity, distributed over 34 sites, each ranging between 10kW and 200MW [1]. The British Energy Security Strategy released in April 2022 stated that the government is preparing to allocate up to £100 million of revenue support to initial electrolytic projects [2]. The current green hydrogen capacity in the UK is only 13MW across 33 sites, highlighting how far the UK must go to reach the new target production of 10GW by 2030 [1].

[1] McCorkindale, Mollie. Green hydrogen investments gain traction as promising UK energy solution. Energy Storage News. [Online] 01 02 2022. [Cited: 18 03 2022.] https://www.energy-storage.news/green-hydrogen-investments-gain-traction-as-promising-uk-energy-solution/.

[2] British energy security strategy. 2022.

**CASE STUDY**

## ITM POWER

ITM Power is trading globally and increasing its project portfolio daily. The company has recently raised £250 million to upscale its hydrogen electrolyser production to support the sharp increase in green hydrogen electrolyser production capacity [1]. This increase in capital investment will help to boost production capacity to 5GW per year by 2024 and make them the joint largest electrolyser manufacturer in the world alongside Germany's ThyssenKrupp.

In January 2021, ITM Power opened its new 1GW PEM electrolyser plant located in Sheffield, which has plans to reduce its production costs by around 40% over the next three years, with the target being to first scale up to 1GW production capacity then to increase as needed [1].

In January 2022, ITM Power announced a 24MW electrolyser sale to Linde Engineering for use in ammonia manufacture [2]. Ammonia manufacturing is a huge market for hydrogen and is seeing a global effort to incorporate low carbon hydrogen sources.

"Decarbonisation of industry is critical to achieving the commitments of countries to reduce greenhouse gas emissions. Globally, the largest use today of hydrogen produced from hydrocarbons is in the production of ammonia for fertilisers. This use has to be curtailed and eventually eliminated. We are very pleased to be working with forward-thinking producers such as Yara and the Norwegian Government to address this issue." [2]

**Dr Graham Cooley**
**CEO of ITM Power**


"THE PROJECT AIMS TO SUPPLY THE FIRST GREEN AMMONIA PRODUCTS TO THE MARKET AS EARLY AS MID-2023, BOTH AS FOSSIL-FREE FERTILIZERS, AS WELL AS AN EMISSION-FREE FUEL FOR SHIPS. GREEN AMMONIA IS THE KEY TO REDUCING EMISSIONS FROM WORLD FOOD PRODUCTION AND LONG-DISTANCE SHIPPING. WITH THIS PROJECT, WE MOVE FROM INTENTION TO ACTIONS TOGETHER WITH LINDE ENGINEERING AND LOCAL CONTRACTORS."

**Magnus Ankarstrand**
**President of Yara Clean Ammonia**

[1] Radowitz, Bernd. ITM raises $343m to boost annual hydrogen electrolyser production to world-leading 5GW. Recharge. [Online] 18 10 2021. [Cited: 18 03 2022.] https://www.rechargenews.com/energy-transition/itm-raises-343m-to-boost-annual-hydrogen electrolyser-production-to-world-leading-5gw/2-1-1084267.

[2] ITM Power. 243MW Sale to Tara. ITM Power. [Online] 26 01 2022. [Cited: 18 03 2022.] https://itm-power.com/news/24mw-sale-to-yara.

Electrolyser manufacturing is fast growing in the UK and Germany, which are homes to the two largest electrolyser companies in the world. There is a global effort to increase gigascale hydrogen production capacity with electrolyser technology. Some of the companies at the forefront of the industry include Cummins/Iberdrola in Spain (1GW), McPhy in France (1GW), Nel in Norway (2GW), which is one of the most established brands, and Plug Power (3GW) in the US, Australia, and South Korea [1].

Several large-scale green hydrogen projects (>50MW) in the UK are in the early stages of development, in either the pre-application planning stage or have submitted a proposal and are awaiting approval [2]. The graph shown in Figure 10 highlights the green hydrogen capacity that is in each stage of development, showing the influx of green hydrogen production anticipated over the next few years.

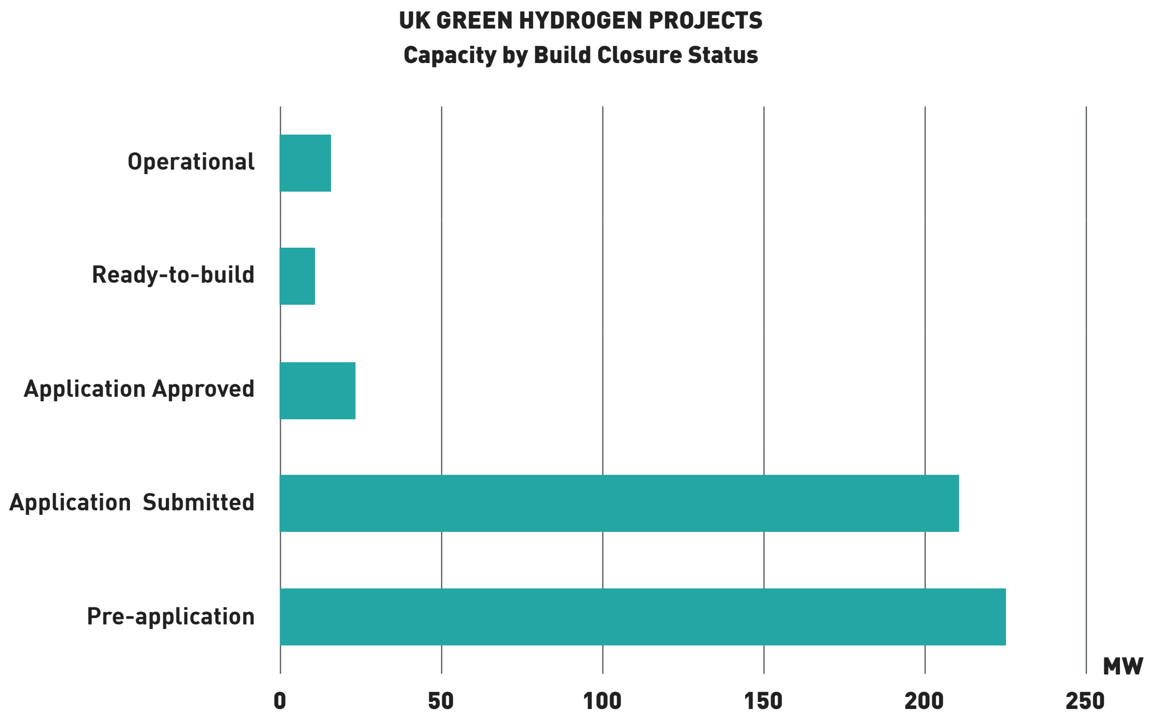



Figure 10: Cumulative hydrogen production capacity shown for UK Green Hydrogen Projects at various stages of development [3].

[1] Radowitz, Bernd. ITM raises $343m to boost annual hydrogen electrolyser production to world-leading 5GW. Recharge. [Online] 18 10 2021. [Cited: 18 03 2022.] https://www.rechargenews.com/energy-transition/itm-raises-343m-to-boost-annual-hydrogen-electrolyser-production-to-world-leading-5gw/2-1-1084267.

[2] McCorkindale, Mollie. Green hydrogen investments gain traction as promising UK energy solution. Energy Storage News. [Online] 01 02 2022. [Cited: 18 03 2022.] https://www.energy-storage.news/green-hydrogen-investments-gain-traction-as-promising-uk-energy-solution/.

[3] UK Green Hydrogen Project Database report, January 2022





Figure 11 shows the cumulative capacity of green hydrogen projects with applications submitted in the UK, showing the year-on-year increase in project capacity up to 2021.

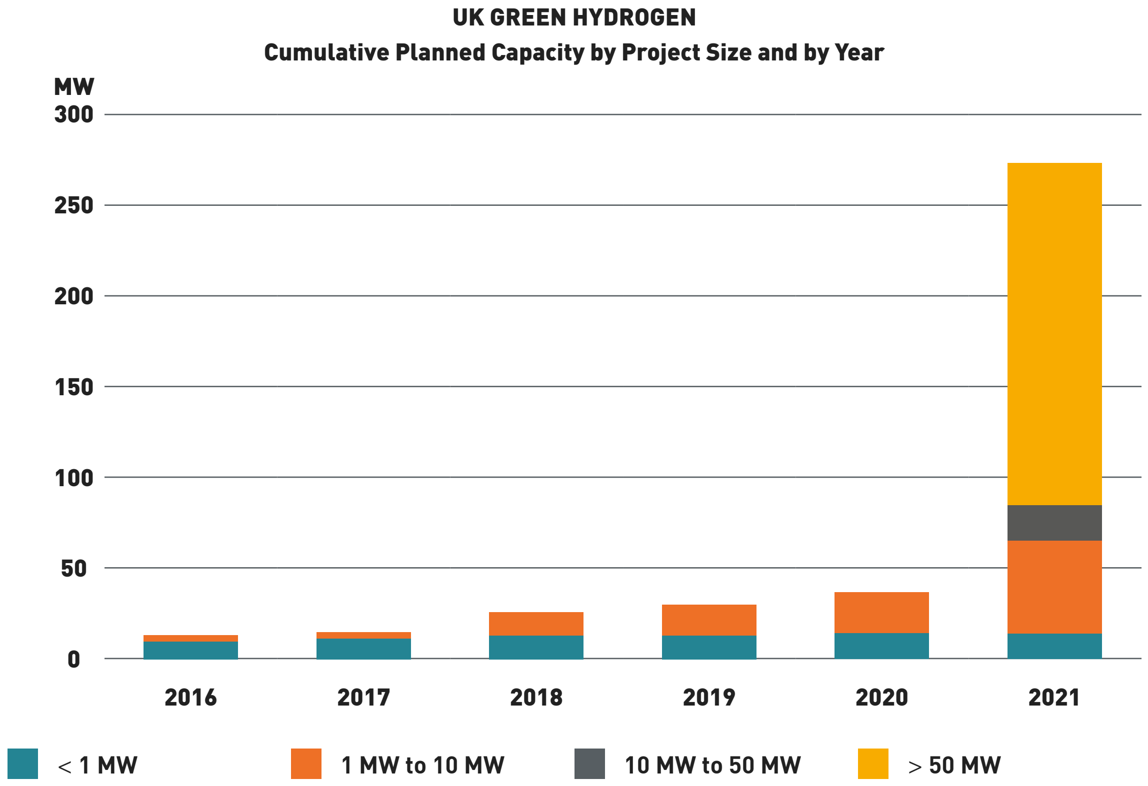



Figure 11: Cumulative hydrogen production capacity for UK Green Hydrogen Projects planned year on year [1].

[1] UK Green Hydrogen Project Database report, January 2022

## SUPPLY CHAIN OPPORTUNITIES FOR A CONTAINERISED ELECTROLYSER

Electrolyser projects will only increase in quantity and will need to see timely developments in manufacturing capabilities and supply chains to meet the demand forecast in the 2050 net-zero scenario. It will require a global focus, and in the 'World Energy Transition Report' released in March 2022 by the International Renewable Energy Agency (IREA), one of the key global priorities is to make green hydrogen production mainstream by 2030, by developing the currently 'niche' market.

A containerised electrolyser system is a popular design for a number of reasons, namely due to the nature of its modular design, and the freedom to increase and decrease production capacity as needed. This design type has been used as an example electrolyser system, however, is merely a guide, and is not the only type of design of electrolyser used in industry.

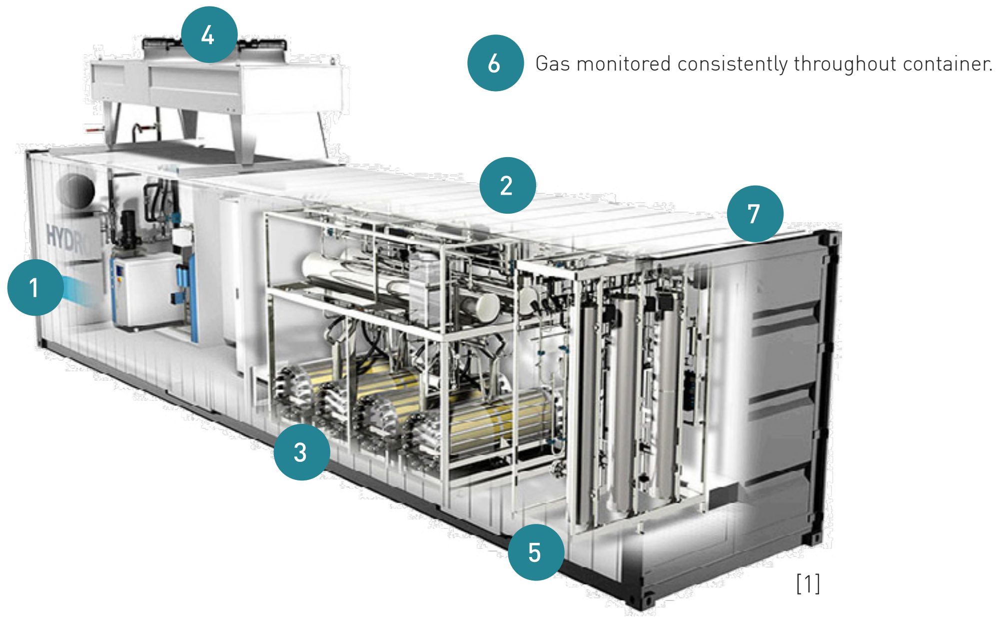
Conducting manufacture in this way is advantageous for several reasons:

- **Increased manufacturability** - the assembly can take place in-house within a controlled environment, reducing the complexity of the on-site manufacturing process.
- **Installation flexibility** - the system can be fitted in the most effective configuration for each application, utilising environmental topology.
- **Simple assembly on-site** - most of the complex manufacturing work has already been completed in a controlled environment.
- **Scalability** - each unit has an assigned capacity, which can be increased as needed by connecting multiple units to an electrical power network in parallel or series.
- **Promotes sustainability** – it is a reusable system, where parts can be upgraded, repaired or changed as needed, without needing to replace the full system.

Modular manufacture of electrolyser systems also comes with advantages for mass production. Integration of Industry 4.0 principles and modern methods of manufacture can provide a sophisticated production line and can generate a controlled product with quality assurance.

Increasing the transparency of electrolyser design makes information about its components more accessible, and therefore allows supply chains to be more easily established. The diagram on page 38 is an overview of an electrolyser system, highlighting the key sub-assemblies.

## CONTAINERISED PEM ELECTROLYSER SYSTEM




## 1. WATER PURIFICATION

### FUNCTION & KEY CONSIDERATIONS

High-purity deionised (DI) water is required in PEM-based electrolysers to ensure an extended stack life. Deionised Water Treatment is the process of removing mineral ions or charged particles from water using ion-exchange vessels.

Typically, a complete water purification system may include several pre-treatments such as filtration, softening and reverse osmosis (RO) membranes that are used in tandem with the DI system to remove contaminates and particulates from water.

It's important to carefully consider material selection within DI water systems. This is to ensure the integrity of water quality and effective integration with the stacks to ensure the integrity of water quality and integration with the stacks. Thermoplastics, such as polypropylene (PP), polyethylene (PE) and polyvinylidene fluoride (PVDF), are widely used for pipework and fittings.

### KEY COMPONENTS

- Adsorption and Mechanical Filters
- Reverse Osmosis Membrane Filters
- Ion-Exchange and Polishing Vessels
- Ultraviolet Disinfection and Water Quality Monitoring
- Reservoirs/Buffer Vessels

## 2. CONTAINERS

### FUNCTION & KEY CONSIDERATIONS

Simple to transport as based upon ISO standard shipping container dimensions. Its design allows the production capacity to be altered through the addition or removal of units in series or parallel. Using a shipping style container also falls with compliance of current lifting and transportation standards.

Modifications of the container are made to ensure separation of the hydrogen bearing equipment and hazardous zones with any non ATEX rated equipment, according to DSEAR regulations.

### KEY COMPONENTS

- Standard ISO containers, modified for integration into PEM system

[1] Energy Magazine. 2022. The future of hydrogen: how to build an electrolyser - Energy Magazine. [online] Available at: https://www.energymagazine.com.au/the-future-of-hydrogen-how%E2%80%8C-%E2%80%8Cto%E2%80%8C-%E2%80%8Cbuild%E2%80%8C-%E2%80%8Can%E2%80%8C-%E2%80%8Celectrolyser/.





## 3. HYDROGEN GENERATION

### FUNCTION & KEY CONSIDERATIONS

Generates hydrogen and oxygen from water using PEM technology.

Large portion of the overall cost isolated in hydrogen stack. Key area of focus is in optimisation of stack design for reduction in cost of manufacturing process and material cost.

### KEY COMPONENTS

- Bipolar plates (Titanium, Graphite Based Composites, Platinum)
- Rubber gaskets
- Membrane Electrode Assembly
- PEM = Proton Exchange Membrane / Polymer Electrolyte Membrane (Nafion, Flemiom, etc)
- Gas diffusion layer (Carbon Fibre)

## 4. COOLING SYSTEM

### FUNCTION & KEY CONSIDERATIONS

Heat is a by-product of the electrolysis process, which requires a thermal control system. A process cooling system is required to remove excess heat from the system and ensure proper operation.

Chiller units supply coolant to the hydrogen purification system.

### KEY COMPONENTS

- Air Blast Coolers
- Heat Exchangers
- Chillers

## 5. PUMPS AND GAS SEPERATION VESSELS

### FUNCTION & KEY CONSIDERATIONS

Oxygen phase separator vessels, separate gaseous oxygen from water exiting the stack.

Hydrogen phase vessels separate gaseous hydrogen and water exiting the stack.

Circulation pumps are used to circulate process water through the system.

### KEY COMPONENTS

- $H_2$/Water Separation Vessel
- $O_2$/Water Separation Vessel
- Water Circulation Pump

## 6. CONTAINER GAS MONITORING

### FUNCTION & KEY CONSIDERATIONS

Early detection of build-up of potentially hazardous gas in an enclosed environment is critical for personal safety. Hydrogen is an odourless and colourless gas, therefore having detection in place is important to mitigate chances of explosion. Similarly, oxygen leakage can be dangerous when combined with hydrogen, they react violently together.

Fan systems should be in place to continuously remove gas to the atmosphere. Fans located near any hydrogen bearing equipment ensure proper ventilation and maintain a required number of air changes per hour in hazardous zones.

### KEY COMPONENTS

- Oxygen and Hydrogen Gas Detectors
- Ventilation Fans

## 7. $H_2$/WATER TREATMENT

### FUNCTION & KEY CONSIDERATIONS

Hydrogen purification is required after hydrogen generation to split the resultant hydrogen and water into their constituent parts. A hydrogen/water separating vessel is used in conjunction with a desiccant drier which removes any remaining water vapour from the hydrogen.

Consideration of materials used in hydrogen systems are important and should adhere to the required operating pressures and temperatures, design life, availability, and corrosion resistance.

Stainless steel (316L) compression fittings are widely used, along with instrument grade tubing/pipework. Welded pipework can be used, typically on larger bores and higher pressures.

### KEY COMPONENTS

- Desiccant Dryer
- Gas Moisture and Quality Monitoring
- Pressure Regulators

Using this schematic of a containerised electrolyser system, an evaluation was completed which looked at the Midlands' regional capabilities across several sectors to supply each component. A workshop was conducted with MTC supply chain experts, in which each component within the sub-assembly groups was evaluated against key sectors which operate in the Midlands. These included aerospace, construction, health care, automotive, energy sector, defence, food and drink, infrastructure, chemical industry and general manufacturing. Each component was given a score, either 0 (component not relevant to expertise), 1 (expertise in the field, could pivot with large investment) or 2 (supply component for a different application, could pivot with minimal investment), as seen in Table 4.

| PROFICIENCY | COLOUR |
|---|---|
| Experience not applicable to component | 0.00 |
| | 0.25 |
| | 0.50 |
| Expertise in the field, could pivot with significant investment | 0.75 |
| | 1.00 |
| | 1.25 |
| Supply component for a different application, could pivot with minimal investment | 1.50 |
| | 1.75 |
| | 2.00 |

Increasing Proficiency

Table 4: Numerical/coloured scale used to describe sectors proficiency in electrolyser supply chain contribution.





This generated a capability matrix with a proficiency number assigned based on the agreement reached within the workshop. To condense the data, an average was taken of the values for each sub-assembly, and the table below was generated.

Table 5 shows the summarised data set generated in the workshop, highlighting the Midlands' proficiency to supply all the components needed for an electrolyser supply chain.

| | Midlands' Industrial Capabilities | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Electrolyser Sub Assemblies | Aerospace | Construction | Health Care | Automotive | Energy Sector | Defense | Food and Drink | Infastructure | Chemical Industry | General Manufacturing |
| Water Purification Systems | 0.80 | 0.00 | 2.00 | 0.40 | 0.80 | 1.20 | 1.00 | 0.00 | 1.80 | 0.40 |
| Power Systems | 2.00 | 2.00 | 0.00 | 2.00 | 2.00 | 2.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| Fan Cooling System | 1.00 | 0.00 | 0.00 | 1.00 | 2.00 | 0.00 | 2.00 | 0.00 | 2.00 | 0.67 |
| Hydrogen Purification | 2.00 | 0.00 | 0.00 | 1.00 | 2.00 | 2.00 | 1.00 | 0.00 | 2.00 | 2.00 |
| Hydrogen Pipework | 1.50 | 1.00 | 2.00 | 2.00 | 1.50 | 1.50 | 2.00 | 1.00 | 2.00 | 1.00 |
| Hydrogen Generation | 1.33 | 0.00 | 1.33 | 1.33 | 1.33 | 2.00 | 0.33 | 0.00 | 1.33 | 1.33 |
| Shipping Containers | 0.00 | 2.00 | 0.00 | 0.00 | 0.00 | 2.00 | 0.00 | 0.00 | 2.00 | 2.00 |
| Container Gas Monitoring | 2.00 | 1.00 | 1.00 | 2.00 | 1.00 | 2.00 | 0.00 | 0.00 | 0.00 | 1.00 |
| Pump and Gas Separation Vessels | 0.33 | 0.67 | 0.67 | 1.33 | 1.67 | 0.33 | 1.00 | 0.67 | 2.00 | 2.00 |
| Ancillary Equipment | 2.00 | 2.00 | 0.00 | 0.00 | 2.00 | 2.00 | 2.00 | 0.00 | 2.00 | 0.00 |
| Total Sector Average | 1.30 | 0.87 | 0.70 | 1.11 | 1.43 | 1.50 | 0.93 | 0.17 | 1.51 | 1.04 |

Table 5: Proficiency of Midlands' industrial sectors to provide componentry for each electrolyser sub-assembly, with proficiency defined as stated in Table 4.

The Midlands region has a wealth of expertise that is distributed across several different sectors, all with capabilities that could contribute to building a hydrogen value chain. The chemical industry, defence, energy sector and aerospace have the largest capacity to contribute to a containerised electrolyser supply chain, as described in the example by the 'Sector Average'. Fuel cells and other electrolyser technologies have similar components and could also utilise this supply chain.

The experience and capabilities used throughout other aspects of their business would be sufficient to support a pivot to the hydrogen sector and could become an addition to their product portfolio. Entering new and emerging markets can be lucrative, and allows companies to operate a more balanced product range output leveraging their expertise to accelerate the development process through the technology readiness levels (TRL).





Table 6 shows the cumulative value of each sector's ability to provide components for each sub-assembly, which is then colour coded dependent on the Midlands' overall proficiency in providing the components for that sub-assembly.

This is useful as it highlights that all components could be supplied by organisations in the Midlands and that this is an opportunity to be seized by the manufacturing industry.

| PROFICIENCY | COLOUR |
|---|---|
| Water Purification Systems | |
| Power Systems | |
| Fan Cooling System | |
| Hydrogen Purification | |
| Hydrogen Pipework | |
| Hydrogen Generation | |
| Shipping Containers | |
| Container Gas Monitoring | |
| Pump and Gas Separation Vessels | |
| Ancillary Equipment | |

Table 6: The general ability for each sub-assembly to be supplied by the Midlands.

It is worth mentioning that the containerised PEM electrolyser system in this exercise is just one electrolyser design type, and that different designs contain different sub-assemblies and components. In addition, the workshop could not represent specialists from each sector and the inclusion of additional technical experts may identify additional capabilities.

### EXPORT OPPORTUNITY

The Midlands has a wealth of experience across a huge range of industrial sectors, which can be leveraged by companies globally. Helping to progress low carbon technologies in other parts of the world has a net positive effect and is made easy today with the advent of remote working.

CASE STUDY

## FORTESCUE FUTURE INDUSTRIES

### GREEN HYDROGEN

The MTC has supported Australian company Fortescue Future Industries (FFI) in its goal of producing 15 million tonnes of green hydrogen annually by 2030. This is an important milestone in international trade, highlighting that location no longer limits companies' abilities to deliver technical assistance.

Green hydrogen is an integral part of the FFI net-zero plans for both industry and transport and has resulted in a goal for rapid upscaling of production capacity. The MTC utilised core skills of design for manufacturing and factory optimisation to catalyse the growth of FFI's green agenda.

The UK will play a further part in the project via JCB and Ryze Hydrogen, who have partnered with FFI to explore a potential offtake and distribution agreement. They will together manage hydrogen delivery and customer demand establishment in the UK [1].

The export opportunity is present both in terms of intellectual property (IP) and physical exports. If the UK becomes an international leader in electrolyser manufacture and builds a globally recognisable supply chain, this could have huge export potential from countries who are late to adopt hydrogen and cannot meet the demand when it arises.

[1] S&P Commodity Insights. JCB and Ryze partner with Fortescue on UK green hydrogen supply deal. S&P Commodity Insights. [Online] 01 11 2021. [Cited: 10 04 2022.] https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/110121-jcb-and-ryze-partner-with-fortescue-on-uk-green-hydrogen-supply-deal.





### TECHNOLOGICAL OPPORTUNITY

Oxidation and reduction at the anode and cathode are restricted by kinetic energy barriers. In order to increase the reactivity at the electrodes catalysts are used, which lower the activation energy needed to initiate a reaction. The development of PEM electrolyser catalysts is a crucial technology that is under investigation globally, as iridium and platinum, the catalysts currently used at the anodes and cathodes, are both expensive and rare [1]. These metals are some of the rarest metals on the planet, and a dramatic increase in electrolyser manufacture would place a considerable strain on their supply chains. To generate 1GW of electricity using a PEM electrolyser approximately equates to a demand of 300kg of platinum and 700kg of iridium using current practices [2]. If PEM electrolysers delivered all the hydrogen needed for electrolysers in the 'IEA net-zero by 2030' target, it would require nine times the current global production of iridium, equal to 63 thousand tonnes [2]. Recycling PEM electrolysers could help contribute to the demand, however, to make a meaningful difference innovation in catalyst materials needs to take place.

### MANUFACTURING OPPORTUNITY

The cost of an electrolyser system is primarily concentrated in the hydrogen stacks (where the hydrogen is generated) and in the 'balance of plant' system (which consists of all supporting components and auxiliary equipment). Industry 4.0 technologies, including the use of automation, robotics and data-driven manufacturing, could be utilised for a reduction in unit cost and lead time. Incorporating these techniques will be critical to upscaling production in-line with the 10GW by 2030 target. Designing to allow active maintenance, where components can easily be replaced or repaired, promotes a circular economy and minimises waste leading to a more sustainable culture of manufacture. This is particularly important for the electrolyser stacks, which is the component group which contains the biggest capital cost.

[1] Current Challenges in Catalyst Development for PEM Water Electrolyzers. M, Bernt, et al. s.l. : Chemie Ingenieur Technik, 2019.

[2] Global Hydrogen Review 2021. Paris : IEA. All rights reserved, 2021.

## THE IMPORTANCE OF A HOLISTIC APPROACH

Integrating hydrogen technology into the economy is a complicated problem. As seen in Figure 1, and as described by the 'chicken and egg' hydrogen problem, each element of the hydrogen value chain is dependent on the preceding element in the chain. Hydrogen production is dependent on distribution, hydrogen distribution is dependent on a market for consumption, and a market for consumption is dependent on both effective hydrogen production and distribution. If the Midlands region seeks to capitalise on the supply chain opportunity presented by electrolyser manufacture, then challenges of delivery and consumption must also be addressed. Focusing on one specific technology area is not going to maximise the overall system implementation, in a similar way that designing a car and focusing exclusively on the engine will not yield a well-rounded solution.

### HYDROGEN STORAGE AND DISTRIBUTION

Hydrogen distribution and storage indirectly support the opportunity for the Midlands region to develop electrolyser supply chains. Improvement in hydrogen infrastructure will enable hydrogen supply to be accessible for consumption, which will therefore increase demand.

The following examples are some of the key technology areas which, if developed, could increase the hydrogen demand by making it more accessible to consumers.

### GASEOUS HYDROGEN - PRESSURE VESSELS

Pressure vessel tanks are the most common method of hydrogen storage, typically stored upwards of 200 times atmospheric pressure (atm) [1], with some high-pressure tanks reaching between 350 and 700 atm [2]. Hydrogen is the lightest gas in existence, which makes its compression necessary, but difficult. Figure 12 shows the relationship between compression energy and gas pressure, for hydrogen, helium, and natural gas (methane). For natural gas, the compression energy remains relatively constant as gas pressure increases, indicating a low energy loss to reach high pressure. Hydrogen on the other hand requires a considerable amount more energy to reach the same pressure as natural gas, making it a much more complex gas to deal with.

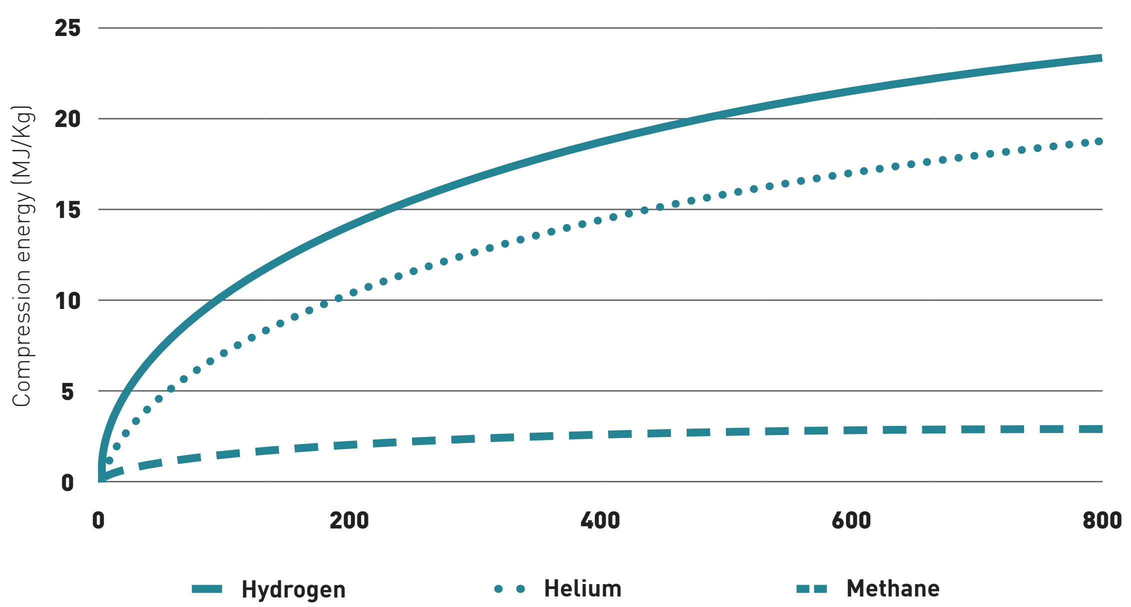



Figure 12: Relationship between compression energy and gas pressure of hydrogen, helium and methane [3].

[1] Robles, J O, Almaraz, S DL and Azzaro-Pantel, C. Hydrogen Supply Chain - Design,Development and Operation / Chapter 2 - Hydrogen Supply Chain Design: Key Technological Components and Sustainable Assessment. s.l. : Elsevier Ltd., 2018. 978-0-12-811197-0.

[2] U.S. Department of Energy. Hydrogen Storage. Energy Efficiency & Renewable Energy. [Online] Energy.gov. [Cited: 2022 01 31.] https://www.energy.gov/eere/fuelcells/hydrogen-storage.

[3] Large-scale compressed hydrogen storage as part of renewable electricity storage systems. AM, Elberry, et al. 29, s.l. : International Journal of Hydrogen Energy, 2021, Vol. 46.



Until recently, thick-walled metallic containers (predominantly stainless-steel alloys) have been the only material that can provide the structural rigidity capable of withstanding the high-pressure needed to deliver adequate energy density. However, these containers are heavy, limiting the ease of transportation. Developments in composite materials have allowed structural components to be reduced in weight across a range of applications, one of these being the development of pressure vessels. High-pressure gas storage is a rapidly growing market for the advanced composite industry, particularly filament-wound carbon fibre composites [1].

Thick metallic pressure vessels have historically accounted for 90% of the market (type I and type II), however, this is beginning to change with type III and type IV becoming increasingly used due to their low weight and increasingly efficient compressed gas storage [1].

- Type III: Thin metal liner, fully wrapped exterior with a fibre-resin composite of high strength and stiffness which supports most of the pressure loading [2]. Maximum pressure 450 bar, half the weight of Type I, double the price [2].
- Type IV: An all-composite structure, polymer liner, commonly polyamide or high-density polythene, which is fully wrapped in a fibre resin composite that supports all of the structural loads, vessel boss and its liner-junction only metallic components [2]. High pressure attainable, very lightweight, high cost [2].


Figure 13: Lightweight Composite Hydrogen Storage Container Types [3].

Using a composite structure greatly reduces the weight, which reduces the energy demand for transportation. Type IV containers were used in the first fuel cell electric vehicles (FCEVs) and held hydrogen at a pressure of 700 atm [4]. Type IV pressure vessels do have a high unit cost, which is mainly attributed to the carbon fibre composite. Reducing the cost of these pressure vessels will play an important role in delivering lightweight transport of hydrogen [4]. To progress this technology, research into alternative high performance and lower cost fibre resin materials can be done through testing resin-fibre matrix combinations under various conditions.

[1] Gardiner, Ginger. Composites end markets: Pressure vessels (2022). CW - CompositesWorld. [Online] 12 03 2021. [Cited: 19 03 2022.] https://www.compositesworld.com/articles/the-markets-pressure-vessels-2022.

[2] Large-scale compressed hydrogen storage as part of renewable electricity storage systems. AM, Elberry, et al. s.l. : International Journal of Hydrogen Energy, 2021.

[3] U.S. Department of Energy. Hydrogen Storage. Energy Efficiency & Renewable Energy. [Online] Energy.gov. [Cited: 2022 01 31.] https://www.energy.gov/eere/fuelcells/hydrogen-storage.

[4] U.S. Department of Energy. Fuel Cell Technologies Office. s.l. : Energy Efficiency & Renewable Energy, 2017.

## LIQUID HYDROGEN - STORAGE TANKS

In terms of properties, liquid hydrogen can be stored at atmospheric pressure, which is very beneficial for structural design and reduces the risk of an explosion. To maintain its liquid state the temperature inside the storage container must not exceed its boiling point of -253°C or 20K, which requires high input energy to reach this temperature and then effective thermal insulation to maintain it (1). As seen in the gaseous hydrogen storage section, gaseous hydrogen is typically stored between 350 to 700 bar, which corresponds to the blue lines as seen in Figure 14. The graph shows how a reduction in temperature yields an increase in density, which therefore increases the energy content per unit volume. The temperature for liquid hydrogen is denoted by the $LH_2$ on the left-hand side of the graph, with a high-density range and at very low pressure.

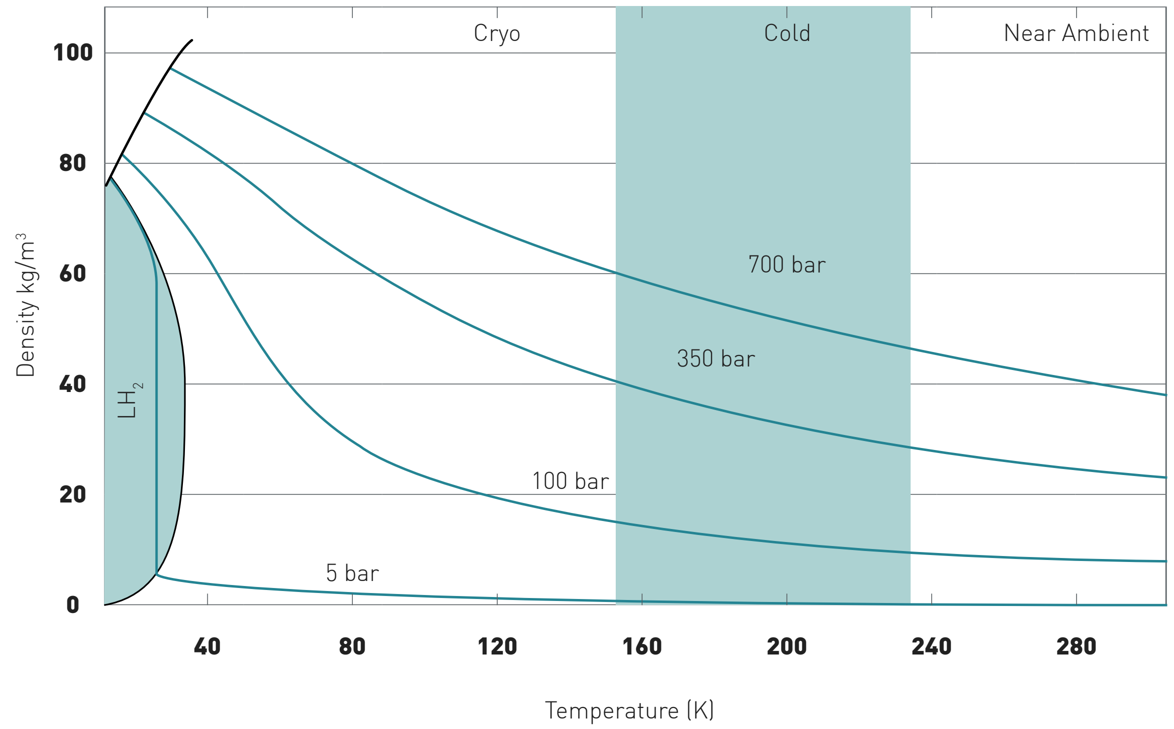



Figure 14: Graph highlighting the relationship between hydrogen density and temperature. ($LH_2$ – Liquid hydrogen, Cryo – Cryogenic Hydrogen) [2].

[1] U.S. Department of Energy. Hydrogen Storage. Energy Efficiency & Renewable Energy. [Online] Energy.gov. [Cited: 2022 01 31.] https://www.energy.gov/eere/fuelcells/hydrogen-storage.

[2] U.S. Department of Energy. Fuel Cell Technologies Office. s.l. : Energy Efficiency & Renewable Energy, 2017.





Maintaining the conditions needed for liquid hydrogen is typically achieved using metallic double-walled containers, where a vacuum separates the inner and outer walls to ensure minimal thermal conduction [1]. Generating liquid hydrogen could be more efficient, as currently the energy loss incurred from converting gaseous hydrogen to a liquid is close to 30% of the heating value [1]. Evaporation, sometimes called "boil-off", is also a loss incurred when stored for long periods, typically when small tanks are used with high surface-to-volume ratios [2].

## NATIONAL HYDROGEN NETWORK

Pipelines have delivered a steady gas stream to heat UK homes for decades, which has resulted in a complex pipe network that spans regional and national connections. One advantage of using a pipe network to deliver hydrogen is that the actual volume of all the pipes in the networks offers a rather considerable storage system. Once the initial capital cost has been overcome to install the infrastructure, gas can be delivered at a very low unit price. One of the lowest cost options is polythene pipework, which is currently being laid throughout the UK in anticipation of a hydrogen economy.

[1] Robles, J O, Almaraz, S DL and Azzaro-Pantel, C. Hydrogen Supply Chain - Design,Development and Operation / Chapter 2 - Hydrogen Supply Chain Design: Key Technological Components and Sustainable Assessment. s.l. : Elsevier Ltd., 2018. 978-0-12-811197-0.

[2] Liquid Hydrogen Delivery. Hydrogen and Fuel Cell Technologies Office. [Online] Energy.gov. [Cited: 2022 02 01.] https://www.energy.gov/eere/fuelcells/liquid-hydrogen-delivery.

CASE STUDY

## CADENT GAS UPGRADING TO HYDROGEN-READY PIPELINES

Cadent Gas is working to upgrade the gas network from iron-based pipes to plastic (polyethylene) pipes. Although the project was originally established to replace ageing cast iron pipework, this work is effectively now making the extensive lower pressure gas network better for carrying hydrogen. Today approximately 75% of Cadent's overall network has been replaced with plastic. While the proportion converted to date varies by geography, this figure is expected to increase to over 92% by 2032. [1] This is not to say that the gas network needs to be entirely plastic in order to carry hydrogen safely and effectively, however there will be supply chain opportunities for manufacturing companies involved in producing the equipment needed for the future network, such as piping, valves and meters. [2]

Steve Fraser, Chief Executive of Cadent, said: **"Achieving hydrogen's full potential will require collaboration with industry and Government to deliver regulatory frameworks that enable the blending of hydrogen into the gas grid and support new hydrogen infrastructure. Hydrogen production will need to be scaled up and investment secured. We believe this should be aligned with a mandate to introduce 'hydrogen-ready' boilers as soon as possible."**

**Steve Fraser**
**Cheif Executive of Cadent**

If a national 100% hydrogen network was installed it would require a large amount of investment to convert the existing network to be hydrogen ready, where a sizable portion of the investment would be spent on research and development. As previously mentioned, one of the main barriers to switching natural gas pipes to a hydrogen stream is the damaging effects of pipe embrittlement, which means only certain pipes can be used to transport hydrogen. There is an opportunity here for research and technology organisations (RTOs) to communicate with businesses in the region, clarifying where the direction of technology is heading and allowing suppliers to be kept up to date with how the needs of the sector change. This could be with respect to pipe material, conversion of pipes to hydrogen-ready equipment, or the development of hydrogen-ready compressors which meet the design criteria for a hydrogen network.

The difference in density of hydrogen and natural gas would also make for changes in the gas network. Because hydrogen is much less dense than methane, it would need to be pumped through the network much faster to maintain the same overall energy densities. The pumps in the system would need to be able to deliver greater compressive power and may need to completely change the current natural gas pumps to accommodate a full hydrogen network. This is an opportunity for RTOs and universities to collaborate with gas companies to decipher design constraints and let innovation be driven by the needs of the industry.

[1] Cadent. Developing networks for the future. 2021.

[2] Cadent launches Hydrogen 10 Point Plan. Cadent - Your Gas Network. [Online] 11 10 2021. [Cited: 28 02 2022.] https://cadentgas.com/news-media/news/october-2021/cadent-launches-hydrogen-10-point-plan.





## HYDROGEN CARRIERS

Hydrogen carriers are compounds that contain hydrogen molecules in high densities, and are simpler to transport. Highlighted in Figure 12, compressing hydrogen to increase energy density requires large amounts of energy, and results in a highly explosive vessel. Similarly, liquefying hydrogen by cooling it to -253°C takes large amounts of energy and is difficult to deal with.

An important area of study in the hydrogen industry is looking into alternative hydrogen carriers which can reduce the difficulty of transportation. Figure 15 shows some of the leading hydrogen storage technologies. The chemical and light metal hydrides show the largest energy density and are among the highest percentage by weight.

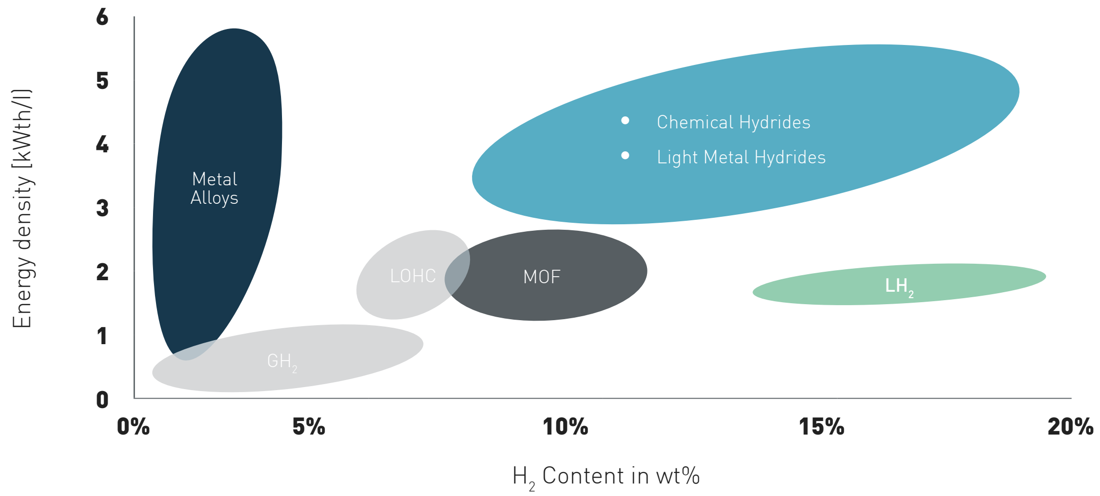



Figure 15: Hydrogen Energy Density vs. Hydrogen Content Percentage by Weight (wt%), (LOHC – Liquid Organic Hydrogen Carriers; MOF – Metal-Organic Frameworks; $GH_2$ – Gaseous Hydrogen; $LH_2$ – Liquid Hydrogen) [1].

Light metal hydrides are still at a low TRL and are being developed by research organisations globally. In terms of chemical hydride, ammonia is a compound whose transportation is well understood and is widely considered the most viable solution for long-distance hydrogen transport.

### AMMONIA

Long-distance transportation of hydrogen, such as shipping, has limitations on volumetric storage but does not have such a constraint on weight. Ammonia can store hydrogen ions at nearly twice the density per unit volume of liquid hydrogen, with a steep reduction in handling complexity, from -253°C ($LH_2$) to -10°C (ammonia) with a small increase in pressure [2]. Ammonia infrastructure is operational today which facilitates its storage and distribution, and one of the main advantages is the large increase in safety when compared to compressed hydrogen. The use of ammonia as a hydrogen carrier is still being researched globally and is another opportunity for RTOs to collaborate and decipher how best to meet the needs of the industry.

[1] Seasonal storage and alternative carriers: A flexible hydrogen supply chain model. Reuß M, Grube T, Robinius M, Preuster P, Wasserscheid P, Stolten D. 2017, Vols. 200:290-302.

[2] The colours of hydrogen routes (The many shades of hydrogen). RINA. 2021.

## COST OF DISTRIBUTION

Storage and distribution of hydrogen is one of the most difficult challenges to be addressed by a hydrogen economy. One of the key material characteristics of hydrogen bearing equipment is its resistance to hydrogen embrittlement, a reaction that takes place between hydrogen atoms or ions and the metal surface. It affects the strength and durability of components and can cause components to fail prematurely. Only a handful of materials, including polythene and some stainless steel, aluminium, and copper alloys, are resistant [1].

In many cases hydrogen is produced near to its area of consumption to mitigate the challenges of transportation, however, with increased adoption, these issues must be addressed. The examples have described gaseous hydrogen, liquid hydrogen, pipe network and hydrogen carriers (ammonia), which all have varying costs depending on the distance. The UK spans just under 1000km, meaning Figure 16 is a good representative of how the price of delivery fluctuates dependent on the distance travelled. The unit cost of hydrogen is proportional to the distance travelled for each distribution method and varies dependent on the means of travel.

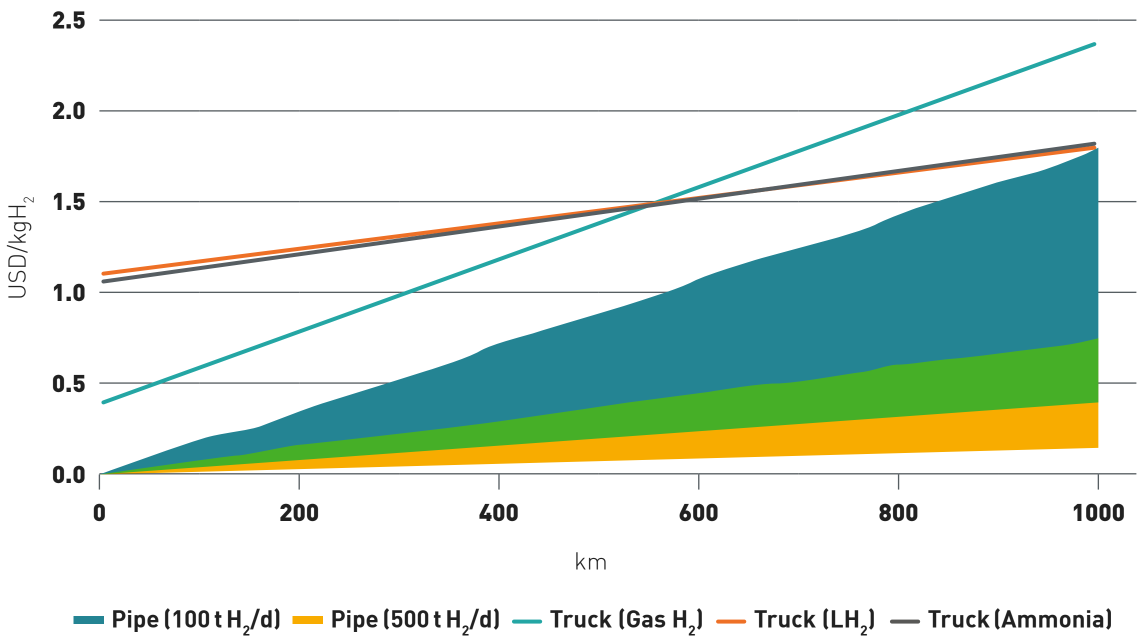



Figure 16: Estimated unit cost of hydrogen transport via 5 means of hydrogen transportation (Pipe capacity referred to as tonnes of hydrogen per day, t $H_2$/d, $LH_2$ = liquid hydrogen, the lower limit for pipeline costs corresponds to repurposing existing pipelines, the upper one to building new pipelines, the transport costs for trucking is based on a capacity of 10 t $H_2$/d, in the case of liquefied hydrogen and ammonia, they include conversion and reconversion costs [2].

[1] Large-scale compressed hydrogen storage as part of renewable electricity storage systems. AM, Elberry, et al. s.l. : International Journal of Hydrogen Energy, 2021.

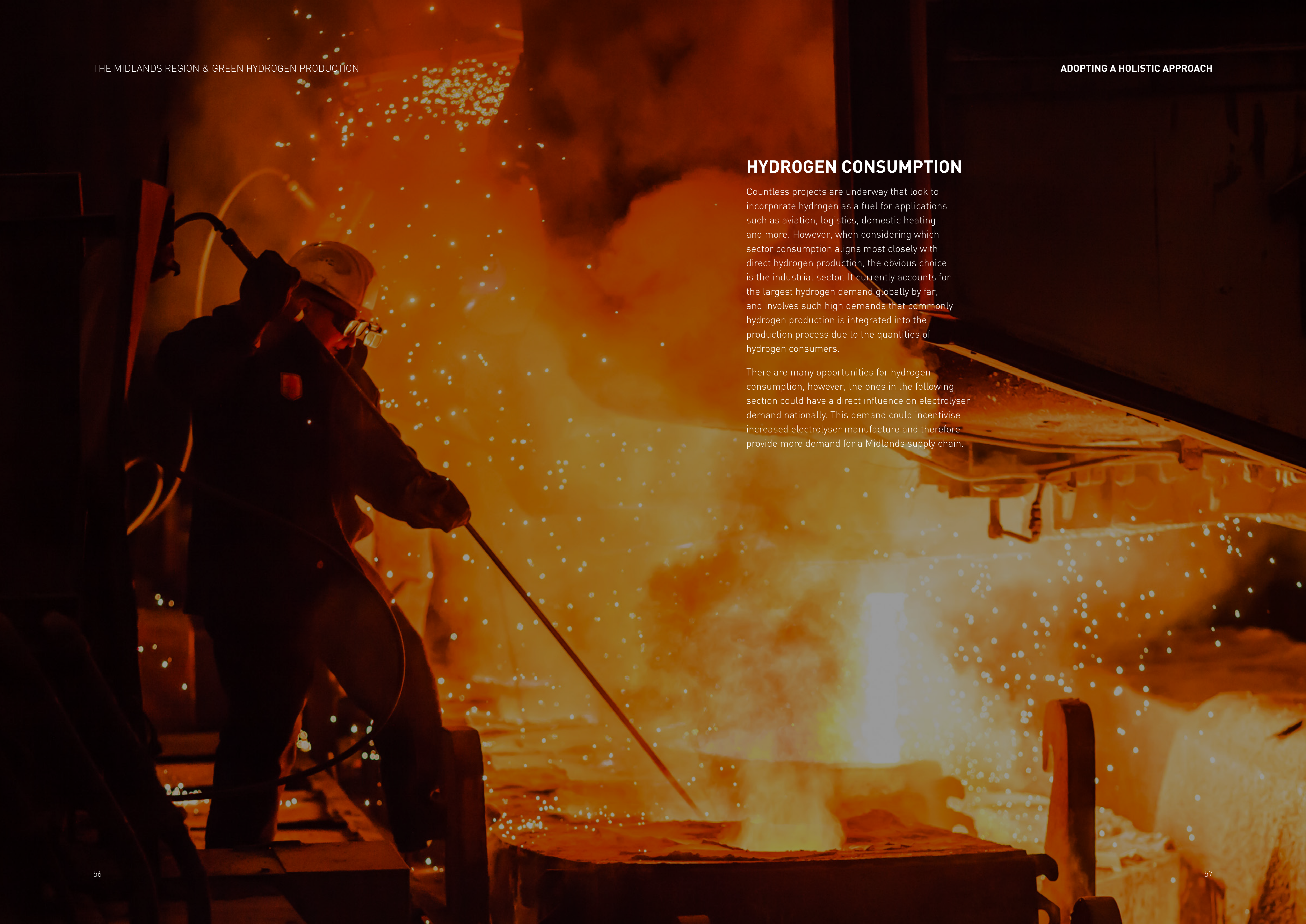
[2] Global Hydrogen Review 2021. Paris : IEA. All rights reserved, 2021.





Transporting hydrogen by truck is inherently more expensive than through a hydrogen ready pipe network for several reasons, including the cost of the truck itself, the hydrogen containment vessel, the driver's time, the safety standards associated with transporting highly flammable gas/liquid, the cost of logistics and vehicle maintenance. As seen in the graph, the liquified hydrogen and ammonia have an initially high capital cost, but over the distance travelled, achieve economies of scale due to the high fuel density deliverable. Trucking in this way is only beneficial for long-distance travel over around 500km, which is the point that the price of transporting gaseous hydrogen surpasses liquid hydrogen and ammonia.

The graph of the hydrogen pipeline shows two limits: the upper limit represents the price for the new pipework and the lower limit represents the price for repurposing the existing national pipelines. The 100 tonne of hydrogen per day pipeline (t $H_2$/d) yields unit hydrogen costs just over double the 500t $H_2$/d pipeline at the upper limit of 1000km. This is again a case of economies of scale, where the less dense fuel types do not deliver the same saving when compared to a higher gas delivery rate.



## HYDROGEN CONSUMPTION

Countless projects are underway that look to incorporate hydrogen as a fuel for applications such as aviation, logistics, domestic heating and more. However, when considering which sector consumption aligns most closely with direct hydrogen production, the obvious choice is the industrial sector. It currently accounts for the largest hydrogen demand globally by far, and involves such high demands that commonly hydrogen production is integrated into the production process due to the quantities of hydrogen consumers.

There are many opportunities for hydrogen consumption, however, the ones in the following section could have a direct influence on electrolyser demand nationally. This demand could incentivise increased electrolyser manufacture and therefore provide more demand for a Midlands supply chain.

## AMMONIA MANUFACTURE

Hydrogen produced for the chemical sector is predominantly consumed by ammonia production and accounts for 84% of the demand [1]. The Harber-Bosch process is well understood, and the bulk of the process emissions are from hydrogen production, typically made from fossil fuels without carbon capture. The process is summarised in Figure 17, where low carbon hydrogen is being proposed to replace the grey hydrogen currently used throughout the industrial sector.

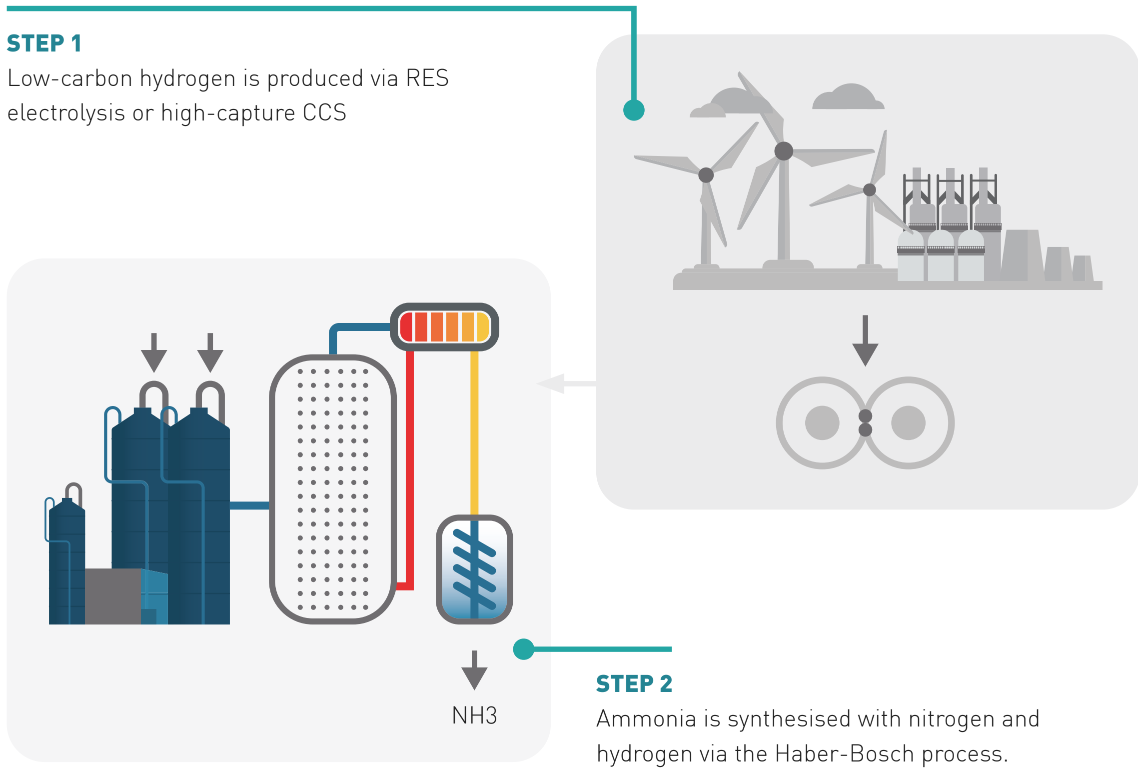



Figure 17: Ammonia production via Harber-Bosch process (RES = Renewable Energy Power Supply, CCS = Carbon Capture and Storage) [2].

As the demand for hydrogen in the industrial sector is one of the highest in all sectors, there needs to be a drive to source low carbon hydrogen to support these industries as a priority, as this application, unlike others, has a clear and consistent demand now.

This emphasises the importance of developing accessible low carbon hydrogen at scale, which the Midlands contains the industrial capabilities to support.

[1] Assessment of hydrogen direct reduction for fossil-free steelmaking. Vogl, Valentin, ÅhmanLars, Max and J.Nilsson. s.l. : Journal of Cleaner Production, 2018, Vol. 203.

[2] Bellona. Hydrogen use in Industry. 2021.





## IRON AND STEEL MANUFACTURE

The iron and steel industry is one of the most polluting sectors in the UK, with the two primary steel production facilities generating a combined 11 million tonnes of $CO_2$ in 2017, translating to around 15% of total industrial emissions [1]. Although steel is not manufactured at scale in the Midlands, there are a large number of manufacturers in the region that depend on its supply. Midlands manufacturers could use their influence to support steel production companies in their journey away from fossil fuels. Globally the sector is directly responsible for emitting 2.6 gigatonnes of $CO_2$ annually, 7% of the global energy system total and a higher pollution rate than all road freight. This is due to the difficulty associated with separating iron from its ore, which requires a large amount of both input energy and carbon.

A more sustainable alternative to the current fossil fuel blast furnaces is suggested in the Industrial Decarbonisation Strategy. It is a process called hydrogen-based direct reduction of iron (DRI), in which hydrogen is used to reduce the iron ore as opposed to coke, which is derived from coal. The complete process could use renewable electricity to power an electrolyser, yielding a hydrogen source; the hydrogen acts as a replacement for the coke and reacts with the iron oxide to reduce it, producing sponge iron as its product. The primary by-product of the reaction is water vapour, which can be recycled back into the hydrogen electrolyser, and due to the sponge iron composition, it does not need to enter a blast furnace; it can be placed into an electric arc furnace (EAF) along with recycled scrap iron, limestone, and carbon, to give usable steel. The emissions associated with this process are 2.8% of those in the conventional 'coking coal' process, provided the hydrogen was manufactured using renewables [2]. In addition to the reduced emissions, this could be a clear use case for hydrogen storage from renewable energy, and incentivises the use of hydrogen for renewable energy spare capacity.

**STEP 1**
Low-carbon hydrogen is produced via RES electrolysis or high-capture CCS.

**STEP 2**
Hydrogen is used to strip the $O_2$ from the iron ore (iron oxides, most commonly $Fe_2O_3$).

**STEP 3**
The resulting iron (Fe) is added to an electric arc furnace and mixed with scrap steel.

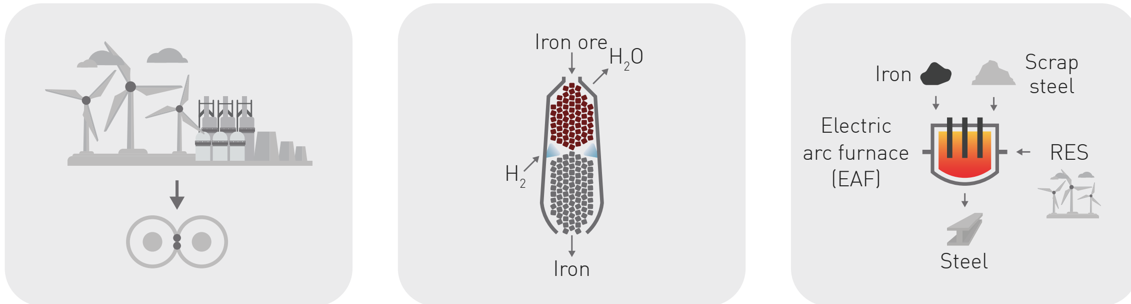



Figure 18: Process of direct reduction of iron (DRI) for low carbon steel manufacture (RES = Renewable Energy Power Supply , CCS = Carbon Capture and Storage) [3].

[1] HM Government. Industrial Decarbonisation Strategy. London : HM Government, 2021.

[2] Assessment of hydrogen direct reduction for fossil-free steelmaking. V., Vogl, M, Åhman and Nilsson, L.J. 2018, Journal of Cleaner Production, Vol. 203, pp. 736-745.

[3] Bellona. Hydrogen use in Industry. 2021.

Using EAF and DRI is already a part of the UK Government's industrial decarbonisation strategy to address the pollution of the iron and steel industry [1]. Figure 19 shows the IEA's projection of steel production by technology, highlighting a steep increase in the prevalence of EAR use in steel production.

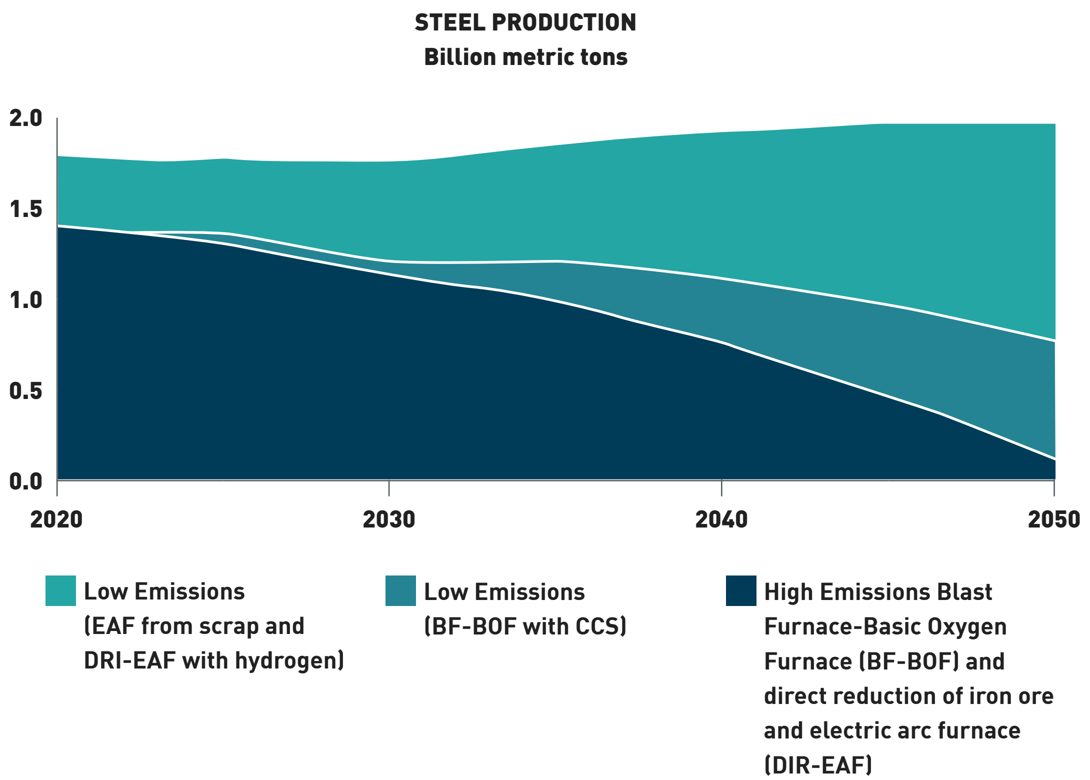



Figure 19: IEA's Net Zero Emissions by 2050 target for the steel industry, highlighting the forecasted steel production by technology from 2020 to 2050 [2].

EAF requires a high amount of electricity to operate, which would mean that the electrical infrastructure would need to be changed if adopted at conventional iron and steel manufacturing sites. In addition to being an opportunity to supply domestically, this is an export opportunity that can be realised by the global market.

[1] HM Government. Industrial Decarbonisation Strategy. London : HM Government, 2021.

[2] McKinsey & Company. The net-zero transition. 2022.





**OIL REFINERY**

As highlighted in the introductory section, refineries are among the highest producers and consumers of hydrogen, with UK-based refineries having dealt with the gas for over 60 years [1]. It is a critical part of the refinery process and is used to remove sulphur content from the oil, a practice that is well matured and long-standing. The remainder is commonly met from on-site production, or hydrogen externally sourced, made primarily with natural gas reforming without carbon capture. This is the market that low carbon hydrogen production can target as a consumer.

The UK is home to six oil refineries, five of which are working to incorporate measures to reduce the carbon output of their on-site hydrogen production facilities, setting an example to oil refineries around the world [2]. Each refinery is different and brings with it varying engineering challenges based on the plant design, geographical location, access to low-cost electricity from renewables and accessibility to carbon storage [2].

Phillips 66's Humber refinery is the only UK facility to have announced plans to establish renewable hydrogen production using the company's 100MW Gigastack project with collaboration between Denmark based Orsted and UK based ITM [2].

Four refineries including Ineos' Grangemouth chemicals complex, Prax's Lindsey site, ExxonMobil's Fawley refinery and Essar's Stanlow refinery are looking to incorporate carbon capture and storage (CCS) technology with their existing sites. Although Prax has not formally announced project plans, it is said to be looking into green hydrogen production at Lidsey [2] Lastly, the Valero's Pembroke facility, which is a member of the South Wales CCS cluster, but not yet been selected for government funding, however is working to decarbonise its production process [2].

[1] UKPIA. Hydrogen. [Online] 2019. [Cited: 16 03 2022.] https://www.ukpia.com/future-vision/hydrogen/.

[2] argus. Low-carbon hydrogen gathers pace in UK refineries. argus. [Online] 22 02 2022. [Cited: 16 03 2022.] https://www.argusmedia.com/en/news/2304469-lowcarbon-hydrogen-gathers-pace-in-uk-refineries.

CASE STUDY

## REFHYNE

The initial REFHYNE project was launched in 2018 with a budget of $16 million, a pan-European project which supported the development of green hydrogen production to decarbonise refineries. The project is set to run until December 2022 and has been funded by the European Commission's Fuel Cells and Hydrogen Joint Undertaking (FCH JU). It is supported by European Union's Horizon 2020 research and innovation programme, Hydrogen Europe, and Hydrogen Europe Research [1]. The project is being run by ITM Power, Shell Deutschland GmbH, SINTEF, Element Energy, and Sphera [1].

In July 2021 a key milestone was reached, with the opening of the 10MW REFHYNE PEM electrolyser, targeted to produce 1,300 tonnes of green hydrogen annually. The site was built by ITM at the Shell Energy and Chemicals Park Rhineland in Wesseling, Germany [1], and is the largest green hydrogen facility in Europe. This is only possible with a low-cost renewable energy source. The UK is a global leader in renewable energy production from wind [2] meaning it has the potential to deliver low-cost feedstock electricity which could be translated into a sustainable hydrogen supply, of course, dependent on demand, although the opportunity in the future is there. The hydrogen produced in this project will support the desulphurisation process of fuels in the refining of oil into usable fuels.

Following the project's success, the REFHYNE II consortium announced in October 2021 funding of $32.4 million to develop a 100MW electrolyser, which will be positioned at the Shell Energy and Chemicals Park [3]. The facility is scheduled to be operational by 2024 and will top its predecessor as the largest project of its kind, with a production capacity of 15,000 tonnes of hydrogen annually [3]. The hydrogen from this plant will help to decarbonise other industrial processes in addition to refineries, as the scale of the project is anticipated to reduce the price of hydrogen, with a goal of 3 euros per kg.

[1] ITM. REFHYNE. IPM POWER. [Online] [Cited: 16 03 2022.] https://itm-power.com/projects/refhyne.

[2] UK Research and Innovation. Harnessing offshore wind. [Online] 24 06 2021. [Cited: 23 03 2022.] https://www.ukri.org/news-and-events/responding-to-climate-change/topical-stories/harnessing-offshore-wind/#:~:text=The%2 UK%20is%20presently%20the,10%25%20of%20the%20UK's%20power.

[3] REFHYNE. REFHYNE II will build the world's largest PEM electrolyser for hydrogen production – an important step towards GW-size electrolyse plants. [Online] 08 10 2021. [Cited: 16 03 2022.] https://www.sintef.no/en/latest-news/2021/refhyne-ii-will-build-the-worlds largest-pem-electrolyser-for-hydrogen-production-an-important-step-towards-gw-size-electrolyse-plants/.





### INDUSTRIAL HEATING

Hydrogen gas can be combusted to provide thermal energy for a range of industrial processes, due to its high temperature and heat flow density. One of the advantages of using hydrogen over other alternatives to a natural gas replacement is that only minor plant modifications would be needed when compared to the incorporation of electrification, CCUS and biomass [1]. Executing a direct swap from natural gas to hydrogen would still be a complex matter due to several fundamental differences in the property of the gas. Hydrogen characteristically has:

- A nonluminous flame and combustion velocity - changing combustion characteristics may need additional control systems, sensors, or gas blending
- Lower radiative heat transfer - this is the primary heat exchange method of vacuum furnaces, which requires the addition of alternative materials changing the design of the burners
- A risk of brittleness or corrosion in some metallic components – this will require a comprehensive overview of the on-site gas network [2].

In short, hydrogen is best suited to high heat applications where electrification, CCUS and biomass alternatives are less feasible, due to the reduced complexity and effectiveness of process substitution. According to modelling completed in the 'Hydrogen for Europe' report released by SINTEF in 2019, if the heat source was changed from burning fossil fuel-based materials to a low-carbon hydrogen stream for the steel, cement and chemical sectors, an annual reduction of 85 Mt of $CO_2$ could be seen across Europe [3].

[1] Krupnick, Jay Bartlett : Alan. Decarbonized Hydrogen in the US Power and Industrial Sectors: Identifying and Incentivizing Opportunities to Lower Emissions. s.l. : Resources of the Future, 2020.

[2] International Energy Agency. The Future of Hydrogen - Seizing today's opportunities. Japan : IEA for the G20, 2019.

[3] Reigstad, Gunhild Allard, et al. Hydrogen for Europe - Final Report of the Pre-Study. s.l. : IFPEN and SINTEF, 2019.

## CEMENT MANUFACTURE

The cement industry is a critical component of the construction sector in the UK with a turnover of around £1 billion annually. The industry is run by 12 cement manufacturing sites and two grinding & blending plants, which generate 90% of the UK's annual cement demand. This is a considerable market and a sector that is committed to decarbonising [1]. 40% of the cement manufacturing process comes from the direct combustion of fossil fuels, which could be substituted for a hydrogen fuel if the correct equipment modification was applied [2].

Several cement producers in the UK are investigating new cement types, with different production methods and cement recipes, to greatly reduce the carbon emissions associated with the cement industry. The introduction of hydrogen as a gas heating source for the industrial heating process has been supported by the Department for Business, Energy and Industrial Strategy (BEIS) as part of the Industrial Fuel Switching Competition.

## ALUMINIUM MANUFACTURE

The UK aluminium industry contributed £6.8 billion in gross value added to the economy in 2019 and employs approximately 97,000 jobs across the UK [3]. Looking at the proportion of the jobs by region as shown in the graph in Figure 20, the West Midlands has the highest percentage of employees in the UK, emphasising the important role the West Midlands plays in aluminium manufacture.

In the primary process of making aluminium metal, bauxite ore is converted to aluminium oxide, and then to aluminium, in an energy-intensive process. The secondary production method is via recycling, where scraps are melted and recast. The UK recycling rate for aluminium beverage cans was 82% in 2020 [4], which is a step toward the European Aluminium and Metal Packaging Europe's goal of a 100% recycling rate by 2030 [5].

The recycling of aluminium requires furnaces that operate at around 750°C [6] typically gas-powered [7], which could be retrofitted with elements that could use a hydrogen flame in future. The Hydrogen Economy Outlook released in 2020 estimated that substituting zero-carbon hydrogen at a price of 73p/kg for secondary aluminium manufacture could be a cost-effective decarbonisation strategy, yielding a carbon price of £66/t$CO_2$ [8].

[1] Welcome to the UK Cement Industry. MPA.

[2] McKinsey. Decarbonisation of industrial sectors: the next frontier. 2018.

[3] Fraser of Allander Institute. The Aluminium Industry in the UK. s.l. : University of Strathclyde, 2021.

[4] Alupro. UK Aluminium Beverage Can Recycling Hits Record Breaking 82% in 2020. [Online] 28 04 2021. [Cited: 18 02 2022.] https://alupro.org.uk/uk-aluminium-beverage-can-recycling-hits-record-breaking-82-in-2020/.

[5] European Aluminim and Metal Packaging Group. European Aluminum and Metal Packaging Europe Launch Roadmap Towards 100% Aluminium Beverage Can Recycling by 2030. Brussels : s.n., 2021.

[6] Aluminium. recycle-more.co.uk. [Online] Valpak. [Cited: 18 02 2022.] https://www.recycle-more.co.uk/recycling/aluminium#:~:text=Aluminium%20cans%20that%20are%20recycled,make%20new%20cans%20comes%20out.

[7] Krupnick, Jay Bartlett : Alan. Decarbonized Hydrogen in the US Power and Industrial Sectors: Identifying and Incentivizing Opportunities to Lower Emissions. s.l. : Resources of the Future, 2020.

[8] BloombergNEF. Hydrogen Economy Outlook. 2020.



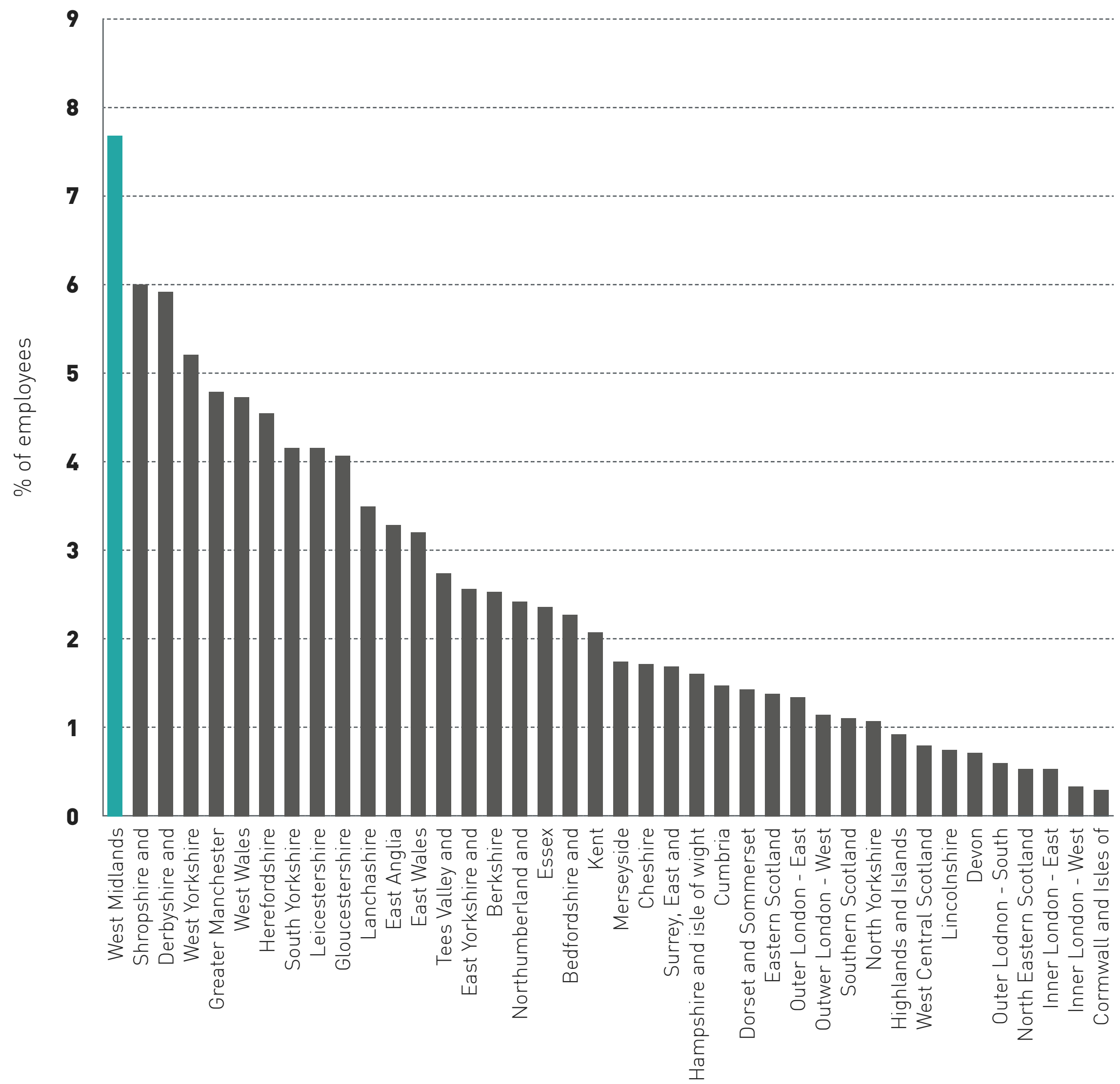



Figure 20: Employment as a percentage by region of the UK for the Wider Aluminium Industries GVA [3].

## GLASS MANUFACTURE

Sand, soda, clarifying agents and limestone are some of the components which make up the glass mix, with around 75% of the glass composition coming from the sand. These materials are ground and run through a production process, whose primary energy demand is derived from the furnace.

CASE STUDY

## PILKINGTON UNITED KINGDOM LIMITED, ST. HELENS

Pilkington United Kingdom Limited based in St. Helens is the world's first 100% hydrogen fired glass production site [1]. Trials began just one week after the release of the UK Hydrogen Strategy in the Liverpool City Region on the production of float (sheet) glass using hydrogen as a replacement for natural gas as the thermal energy provider in the furnace.

The project is part of the 'HyNet Industrial Fuel Switching' programme, led by Progressive Energy, and supplied with hydrogen from BOC. This project is envisioned as the first of many, where the project will look to decarbonise the North West by 2025, using the £5.3 million funding awarded by BEIS [1].

[1] Bodey, Amy. World first as 100% hydrogen fired at Pilkington UK, St-Helens. s.l. : HyNet North West, 2021.





## CLOSING RECOMMENDATIONS

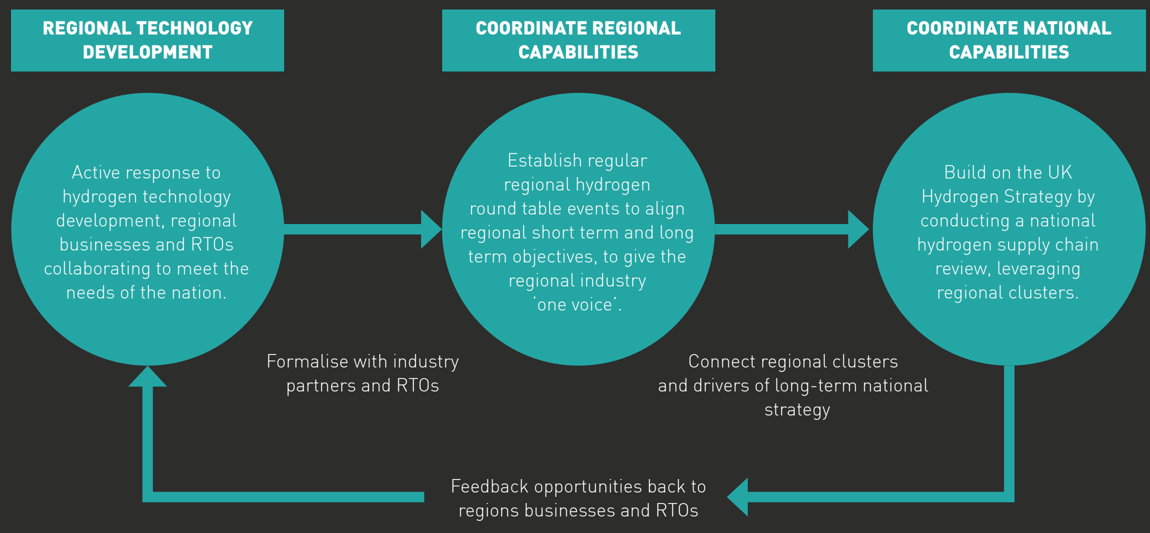
**RECOMMENDATION 1 – GREEN HYDROGEN PRODUCTION**

1. UK aim: Deliver green hydrogen at a competitive price. Carbon taxing will reduce the competitive advantage of GHG emitting hydrogen production. The UK has the capabilities (technical expertise) and resources (access to low-cost renewable energy) to increase green hydrogen production. The UK Government needs to establish knowledge and capability gaps, and devise plans to realise these opportunities. Doing so will prove significant for domestic and international trade as the world realises the potential of hydrogen.
2. Midlands objective: The Midlands region has the industrial capabilities to provide all components and expertise needed for a containerised electrolyser supply chain. Supporting the industry in this way will allow for increased UK electrolyser manufacturing capacity. A hydrogen supply chain is a critical foundation which a hydrogen economy will depend upon. Supply chains are fundamental to manufacturing, requiring action now, by providing businesses with the correct support and guidance in order to increase their maturity, as well as maximising the opportunities when they arise.

**RECOMMENDATION 2 – THE IMPORTANCE OF A HOLISTIC APPROACH**

Industry leaders should work more closely with government to create both short-term and longterm plans and strategies for the industry. These should provide actionable statements formed from value chain analysis, considering the risks and opportunities previously identified. Government should look to support these proposals both financially and operationally, to enable the industry to build competitive advantage.

1. Re-use existing infrastructure where possible. Thermal energy is provided to around 80% of homes in the UK using natural gas (1), resulting in a complex pipe network that spans the entire UK. Substituting hydrogen for natural gas in the network is a difficult challenge for several reasons, mainly the large difference in density and the damage caused to pipework as a result of hydrogen embrittlement. Many gas companies are taking the initiative to substitute pipework with 'hydrogen ready' pipes in anticipation of adoption. Whether the pipe network is used for domestic heating or to cheaply deliver a hydrogen supply across the country, leveraging existing infrastructure is a financially beneficial solution.
2. Decarbonise hydrogen production in the industrial sector. Industrial sectors consume hydrogen in the biggest quantities globally, and need low carbon hydrogen in high quantities now, in sectors such as ammonia manufacture and oil refineries. Decarbonising hydrogen production in these industries will replace grey hydrogen production and should be a priority. Using hydrogen as a fuel in applications such as transport could play a major role in future, but currently, the technology is at a low technology readiness level (TRL) and will not likely draw significant demand for some time.
3. Coordinate and align both regional and national approaches to the production of a hydrogen value chain.




3.1 Active response to hydrogen technology development, regional businesses and RTOs collaborating to meet the needs of the nation. The government needs to provide continued support for first movers and work to address investment risk. This can be achieved by initially supporting cluster projects and pooling capital to allow the highest number of beneficiaries per investment. To support businesses, targeted loans, grants, and other tools can be used to provide the private sector with the resources that it needs to grow a market, distributing both risk and rewards. RTOs must provide businesses with tools to grow the market, where technology development is guided by regional short-term objectives and national long-term aims. Facilitate development by taking an active approach to hydrogen standards and regulation, where safety is prioritised while giving RTOs freedom to safely experiment.

3.2 Establish regular regional hydrogen round table events to align regional short term and long term objectives, to give the regional industry 'one voice'. Having a single entity to coordinate and develop the value chain initially by region, and then combined to form a national map, would help to inform decisions surrounding project placement and enable businesses to fully understand how their region's capabilities compare nationally. If this model was established for all UK industrial regions it would increase visibility and collective direction, providing Britain with a more efficient performance on a global scale.

3.3 Build on the UK Hydrogen Strategy by conducting a national hydrogen supply chain review, by combining regional clusters. The concept of the 'one voice' referred to in point 3.2 is now scaled up on a national level, where the voices of each industrial cluster can be combined nationally to form a complete UK landscape of capabilities and resources. This approach facilitates transparency, allows regions to communicate with the government directly, and allows for short term objectives to be completed by each regional area which aligns with the UK's long term aim.

[1] Roser, Hannah Ritchie and Max. Energy mix. Our World in Data. [Online] University of Oxford, 2020. [Cited: 24 03 2022.] https://ourworldindata.org/energy-mix#citation.

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**A REVIEW OF HOW THE MIDLANDS REGION CAN SUPPORT GREEN HYDROGEN PRODUCTION, AND THE IMPORTANCE OF A HOLISTIC APPROACH**


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