Towards a green hydrogen roadmap for the UK

A summary report

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Towards a green hydrogen roadmap for the UK – summary report

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Executive summary

The role of hydrogen

Low-carbon green hydrogen, produced by the electrolysis of water, has emerged as a leading solution to enable countries to meet their net zero obligations. With a history of use within the petrochemical and fertiliser industries, hydrogen's potential extends across a range of sectors, particularly those which are deemed hard-to-decarbonise, including industry and transport. It can also provide a cost-effective solution for large-scale, long-term energy storage to support renewable electricity generation. This report examines the key developments needed for green hydrogen to transform the UK's energy landscape.

The major obstacle to a green hydrogen economy is transitioning from the existing fossil fuelled economy to a new, low-carbon future that uses hydrogen to power transport, heat industry, defossilise chemicals and store low-carbon energy. Many countries are planning this transition and are developing roadmaps to achieve it. This has created many opportunities for those countries leading the development to emerge as a first mover on the hydrogen economy, including playing a leading role in shaping regulatory standards and opportunities to export technologies.

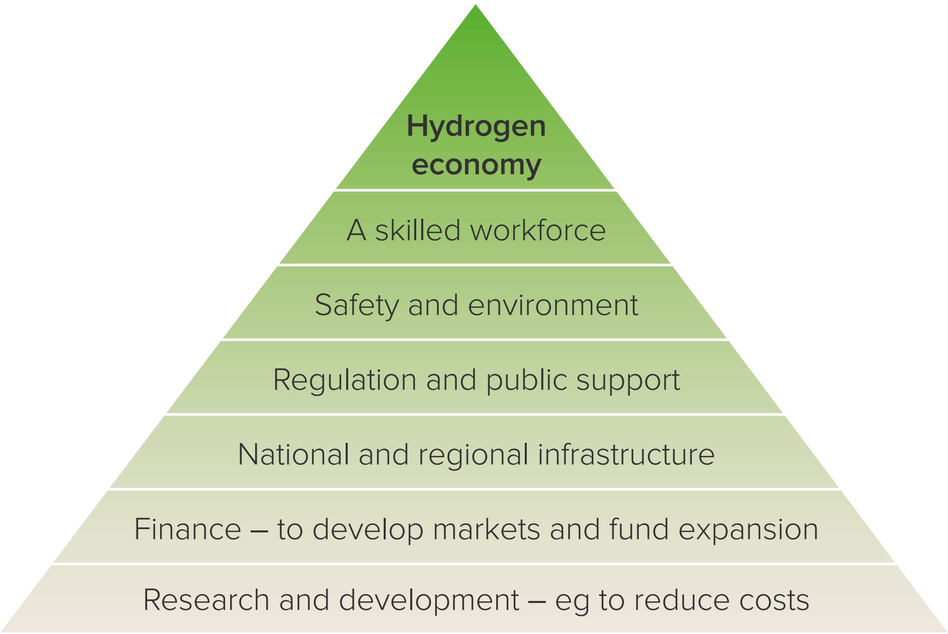
At the time of the workshop, the UK government had set a target to generate 10 GW of low-carbon hydrogen capacity by 2030, with 6 GW coming from green hydrogen. Meeting this target requires a substantial increase in electrolyser installations and innovation, enhanced renewable energy capacity, innovation to improve efficiency and reduce costs, regulatory development, and, crucially, enabling flows of investment. The latter of these must include stimulating demand for hydrogen to ensure investment in production. This must be underpinned by UK excellence in hydrogen research and skills, and a whole systems focus to ensure hydrogen is delivered effectively across each region and industrial clusters.

Building a hydrogen economy

There are several critical factors that need to be in place before hydrogen can usefully replace fossil sources and fuels, as shown in figure 1. table 1, p 40, highlights some of the key challenges and developments against the timeline to achieve this by 2050.

FIGURE 1

Factors for a green hydrogen economy.



The development of a successful hydrogen economy in the UK depends on transitioning from technical maturity to commercial maturity. Whilst R&D is required in some areas, many technologies are sufficiently developed to be useful, but they need to be scaled up.

Scaling up needs substantial investment, which in turn requires policy continuity, economic surety of financial return and the establishment of markets.

To be useful, hydrogen will need to be manufactured, stored and transported to end users. Hydrogen storage and transportation present significant technical hurdles due to hydrogen's low density and high flammable range. The blending of hydrogen into the UK's existing gas network (up to 20% H_2) also offers a transition pathway, but in many areas will depend on upgraded pipe infrastructure. Hydrogen can be stored effectively in bulk in salt-caverns and the UK has suitable geology. The UK will need a planned and co-ordinated national and regional level infrastructure to support the sustainable production and use of low carbon hydrogen across its many potential uses.

Hydrogen and its derivatives offers the potential to decarbonise sectors like transportation, steel manufacturing, and chemical production which cannot be decarbonised with electricity. With increased use in new sectors, hydrogen will require strict safety and environmental controls. The public will also need to be content that it can be produced, stored, and used safely, and tighter regulation and monitoring might be necessary.

Finally, the safe conversion of existing industries and transport modes to hydrogen will require the re-training of many people and an increase in the number of skilled hydrogen engineers, scientists, and operators.

It is important to note that the development of a hydrogen economy cannot be done in isolation from the rest of the economy or indeed the national infrastructure. The production of green hydrogen in bulk relies on the availability of cheap, abundant renewable power and large quantities of clean water, both of which will be, or are currently, in demand. The transition of transport modes to hydrogen or hydrogen-based fuels will require co-ordination both regionally and nationally (and internationally with respect to aircraft and shipping), as will moving industrial heating to hydrogen and chemical production to alternative carbon sources.

The UK may usefully assess likely pathways for the development of the global hydrogen economy (and hydrogen technology markets) and decide the extent of the role the UK wishes to play in these markets. This may help set a direction for the UK's domestic hydrogen development.

Insights

There are three key areas that need to be addressed to ensure that the UK gains the maximum benefit and least disruption from a future hydrogen economy:

I **A roadmap for green hydrogen.**
Building on the existing hydrogen production delivery roadmap, investor roadmap, T&S pathways and national H_2 strategy to deliver a comprehensive detailed hydrogen roadmap for the UK will provide the direction necessary to achieve a successful hydrogen economy.

II **Support for commercialisation and scale up.**
It is important that the roadmap helps to provide long-term confidence and assurance for major capital investment in infrastructure and manufacturing facilities. In addition, refined industry specific roadmaps could be used to influence the creation of fit-for-purpose funding allocations at both a national and regional scale.

III **Co-ordination for development and growth.**
The development of a successful hydrogen economy will necessitate the co-ordination and balancing of hydrogen supply and demand across the country, necessitating the design of a transport and storage system that is flexible enough to accommodate growth at the regional and local levels. This will require collaboration between national and local government, co-ordinated by NESO and aligned with the national hydrogen development goals and Local Area Energy Plans (LAEPs).

In addition, there are several challenges to achieving a future hydrogen economy that will need to be overcome:

IV **Developing and securing the skills needed.**
Ensuring long-term support and commitment for a portfolio of educational strategies.

V **Technical barriers will need to be addressed.**
Through continued R&D, targeting efficiency improvements, material cost / availability / recycling and overall cost reductions.

VI **Developing regulatory frameworks.**
Ensuring safety, minimising environmental impacts and building market confidence, with clear standards and protocols for hydrogen use. These should be standardised at the international level.

VII **Co-ordination.**
The development of a hydrogen economy must be introduced in harmony with other net zero changes, for example to electricity generation and distribution.

VIII **Improving public understanding regarding the safe use of hydrogen.**
Accidents will happen and failure to be open and honest with the public would jeopardise the creation of a hydrogen economy in the UK.

There are many countries around the world that are grappling with the challenges of employing hydrogen to decarbonise their economies. If the UK is seeking to play a leading role in the development and export of green hydrogen technologies, then pace matters as time is short.

This document summarises the discussions and conclusions from a two-day workshop hosted by the Royal Society and Royal Academy of Engineering in January 2024. The workshop looked at the development pathways towards creating a world-class hydrogen economy in the UK. The workshop was made up of experts from academia, industry and government and it identified the critical enablers, barriers, dependencies and opportunities for growing the nascent UK hydrogen sector.

1. Introduction

This report sets out the key barriers and opportunities across electrolytic green hydrogen production, transport, storage, and use, as well as environmental, safety, and system considerations of green hydrogen upscaling. At their request, a set of policy recommendations is included to help meet the Government's ambitions for green hydrogen in the UK and to ensure that it fulfils its crucial role in a secure, reliable, and low-carbon energy system in the future.

It should be noted that the report looks only at the route to a green (electrolytic) hydrogen economy for the UK, which is best suited to a future net zero-compatible UK grid dominated by renewables. Blue hydrogen (produced using natural gas with CCS) is outside the scope of this report.

The report is the summary of the discussions held at a two-day workshop convened by the Royal Society and the Royal Academy of Engineering in January 2024, which brought together participants from industry, academia, and government to identify the key technical and scientific targets, research questions and milestones to be achieved to meet the UK's strategic aims for a green hydrogen economy, as well as potential risks and barriers. For a full list of participants see appendix.

1.1. Why green hydrogen?

Hydrogen is one of the most widely used industrial commodities. The chemical and physical properties of hydrogen make it ideal for use in a range of uses and industries:

1. **Energy transfer**
   Hydrogen can be used as an energy vector, meaning it can be produced, transported, and stored as a means of delivering and / or storing energy at scale, particularly for use in hard-to-decarbonise sectors. It can, in principle, be shipped internationally.
2. **Chemical industry**
   Hydrogen is currently used in several chemical industries, for example in the manufacture of ammonia and plastics. It can also be used to decarbonise the production of iron and steel[1].
3. **Zero carbon fuel**
   Hydrogen can be used to power engines and heaters and only produces water vapour in the exhaust. Examples include jet engines and industrial heating. Green hydrogen is also required in the manufacture of other green fuels, such as green ammonia, methanol or synthetic aviation fuel.

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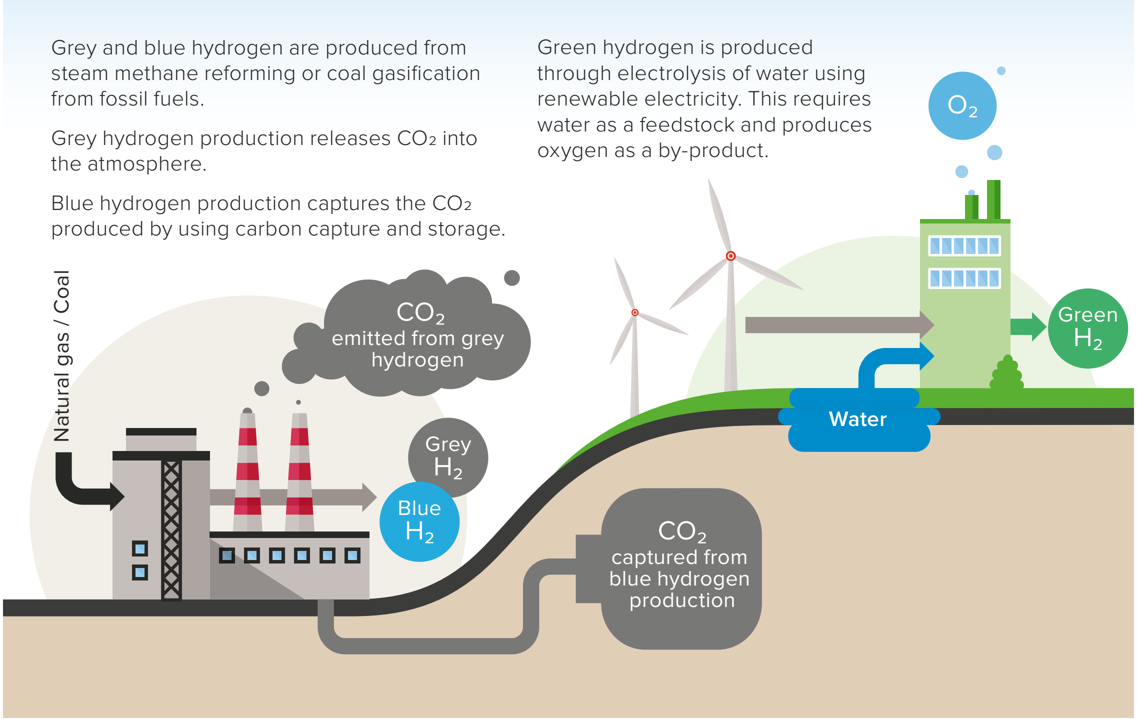
[1] The Royal Society. 2024. Catalysing Change: defossilising the chemical industry. See https://royalsociety.org/news-resources/projects/defossilising-chemicals/ (accessed 24 May 2024).

FIGURE 2

Common methods of hydrogen production



Source: the Royal Academy of Engineering.

Today, around 100 million tonnes of hydrogen are produced globally from unabated coal and natural gas, primarily used to make fertiliser (43%) and refine oil (57%). This use accounts for around 2% of global annual CO_2 emissions[2, 3, 4]. The use of green hydrogen in the net zero transition could see it grow from three to eight times current levels (300 – 800 million tonnes) and create an economy estimated at perhaps as large as $8 trillion globally by 2050, with an associated hydrogen technology market worth up to $1 trillion globally[5]. This would account for up to 12% of global final energy demand[6]. The routes to hydrogen production that are predicted to be the most prominent are shown in figure 2.

Hydrogen is already widely used in industry, produced using unabated fossil fuels ('grey hydrogen'). Beyond green hydrogen, there are other alternative approaches to producing low-carbon hydrogen, including through steam methane reforming using natural gas with carbon capture and storage ('blue hydrogen'), methane pyrolysis ('turquoise hydrogen') and electrolysis powered by nuclear energy ('pink hydrogen'). It is also worth noting that hydrogen can be found in naturally occurring deposits ('white hydrogen'), though its commercial viability is under investigation and further geological exploration is needed to better understand the extent of the role white hydrogen may play in the future hydrogen economy.

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[2] Energy Transition Commission. 2021. Making the Hydrogen Economy Possible: Accelerating Clean Hydrogen in an Electrified Economy.

[3] IEA. 2023. Towards hydrogen definitions based on their intensity.

[4] IEA. 2022. Global Hydrogen Review 2022.

[5] Hydrogen Innovation Initiative. 2024. Hydrogen Innovation Opportunity.

[6] IEA. 2023. World Energy Outlook 2023.

1.2. Green hydrogen in the UK

Low-carbon hydrogen, and in particular green hydrogen, is set to play an important role in the future energy system, as the need to decarbonise in line with the UK's legal commitment to reach net zero greenhouse gas emissions by 2050 gains pace. It can replace the grey hydrogen currently produced in the UK for use as a feedstock to the petrochemical and fertiliser industries, thereby cutting emissions of carbon dioxide to the atmosphere.

Beyond this, the role of hydrogen is set to grow considerably. According to the Climate Change Committee (CCC) Sixth Carbon Budget's recommended 'Balanced Net Zero Pathway'[7], to achieve net zero by 2050, hydrogen use would be comparable in scale to today's electricity use – around 350 TWh a year[8].

Globally, the tide is shifting towards low-carbon hydrogen production as a key future energy vector. By 2030, green hydrogen production capacity could be between 175 – 420 GW globally, based on announced projects[9].

The UK has a hydrogen strategy which was published in August 2021 and updated in December 2023. It contains a package of measures including eleven major new hydrogen projects across the UK, representing £400 million of upfront investment over the next three years and £2 billion in revenue support over the next fifteen years, ensuring a guaranteed price for the hydrogen they supply.

At the time of writing, the UK government's ambition for low-carbon hydrogen is for 10 GW of production capacity by 2030, of which 6 GW is to be green hydrogen[10]. This will require a substantial increase in the UK's electrolyser capacity, development of transport and storage infrastructure, and, crucially identifiable, and scalable end uses across sectors. The UK could emerge as a leader in low-carbon hydrogen production and use, if the components of the hydrogen economy are supported and established at pace. This is achievable; renewable electricity generation would need to increase by approximately 10 GW of predominantly offshore wind to provide the energy needed to meet the UK's green hydrogen targets.

While the UK Hydrogen Strategy takes a 'twin track approach' of scaling up blue and green hydrogen (up to 4 GW and 6 GW of the overall target of 10 GW production capacity by 2030, respectively), this paper focusses solely on the scale up of green hydrogen production and use. While the amounts that blue and green hydrogen will contribute to the future mix will depend on several factors, blue hydrogen's dependence on natural gas as the major feedstock will expose its production to international natural gas price fluctuations and supply issues. Achieving low-carbon, blue hydrogen production depends also on the successful scale up and performance of Carbon Capture and Storage (CCS) and the minimisation of leakage of both natural gas and carbon dioxide. The current cost of green hydrogen production is higher than that of blue hydrogen, falling between an estimated $2.5 / kg – $6.5 / kg in 2020[11], but it is forecast to fall to a level that is cheaper than blue hydrogen over time, due to falling costs for electricity from renewables[12]. The timescale at which parity with blue hydrogen will be achieved is uncertain and will depend largely on economies of scale and supportive policy initiatives.

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[7] In the Sixth Carbon Budget, the CCC developed four exploratory scenarios to explore a range of pathways to achieve net zero by 2050 with different assumptions in the face of uncertainties. The four exploratory scenarios were then used to construct the Balanced Net Zero Pathway as the recommended scenario.

[8] Climate Change Committee. 2020. The Sixth Carbon Budget. p. 138. See https://www.theccc.org.uk/publication/sixth-carbon-budget/ (accessed 21 August 2024).

[9] IEA. 2023. Global Hydrogen Review.

[10] Department for Energy Security and Net Zero. 2021. UK hydrogen strategy. See https://www.gov.uk/government/publications/uk-hydrogen-strategy (accessed 5 July 2024).

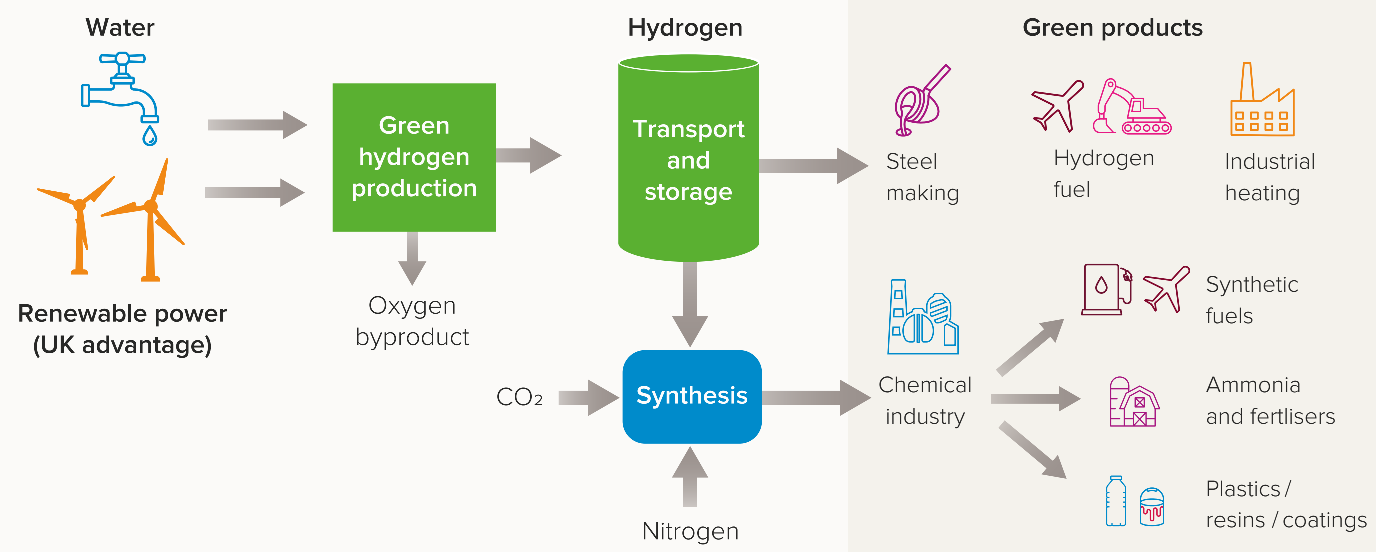
[11] IRENA. 2021. Making the breakthrough: Green hydrogen policies and technology costs. See https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_Hydrogen_breakthrough_2021.pdf (accessed 5 July 2024).

[12] *Ibid*.

FIGURE 3

The full value chain for green hydrogen from inputs to finished green products.

The UK's strengths are a strong science base, access to renewable power and existing expertise within industries.



More broadly, the levelized costs of hydrogen will be dependent on electricity costs, capital costs, and capacity factor, while wider costs like water use will be relatively small[13]. Findings elsewhere suggest that there is a $0.6 / kg decrease in the production cost of hydrogen for every $10 / MWh decrease in the cost of electricity[14].

Green hydrogen is therefore of significant strategic importance, given the twin policy goals of energy security and decarbonisation. Its production, via various forms of electrolysis, is also sufficiently discrete from a technical point of view to warrant its own focus in terms of the scientific, technical, and economic challenges associated with its scale up.

Despite the need and ambition to scale up green hydrogen production and use, there are several significant barriers that need to be addressed. Broadly these are:

- Making green hydrogen supply cost competitive with fossil-based hydrogen and alternatives. Critically, for green hydrogen, this includes the generation and supply of low-cost renewable electricity.
- Grid composition and capacities. Green hydrogen relies on renewable energy. Meeting wind and solar supplies to underpin a green hydrogen economy will require grid scale-up and connectivity.
- Modifying existing processes so that they can use hydrogen as a fuel or feedstock.
- The need to scale up demand as well as production and requisite storage and transport infrastructure.
- Minimising and managing the environmental and safety aspects of hydrogen production, transportation, storage and use at scale.
- Enabling the full value chain within the UK, eg technology and manufacturing value creation (see figure 3). There are decisions to be made as to which value chains to focus on developing, as the UK is unlikely to be able to fully develop full value chains for all possible hydrogen uses effectively.

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[13] Webb *et al*. 2023. The application of green finance to the production of blue and green hydrogen: a comparative study. *Renewable Energy*, 219.

[14] Longden *et al*. 2021. Conditions for low-cost green hydrogen production: mapping cost competitiveness with reduced-form marginal effect relationships. CCEP Working Paper 21-08 August 2021.

2. Advances and challenges in green hydrogen production technologies

This chapter explores the current state of electrolysis technologies that will be pivotal to the production of green hydrogen. The technological and operational scale-up challenges and opportunities were outlined, as well as broader interdependencies and key enablers for electrolytic hydrogen production.

2.1. Electrolyser technologies overview

Electrolysers use electricity to split water into hydrogen and oxygen. Electrolysis functions by sending an electric current from a negatively charged electrode through a solution containing water and a divider, to a positively charged electrode. As the process of electrolysis splits the water into hydrogen and oxygen, the divider separates one from the other. The hydrogen gas that is produced in this process is then captured, purified, dried, and compressed ready for use. Oxygen is produced as a byproduct.

The success of green hydrogen will rest upon the widespread availability of cheap renewable electricity and the deployment and integration of low capital cost and efficient electrolyser technologies.

There are four primary challenges common to all electrolyser types. These are:

- **Economic challenges.**
  High electricity prices and high production costs are not conducive to upscaling, operating, or attracting investment for electrolysers. Electricity costs are estimated to account for up to 75% of the cost of green hydrogen[15]. Innovation as well as clarity from government will help attract investment. Given that input energy costs are a large proportion of production costs, and renewable electricity is an input requirement for green hydrogen, the availability of low-cost renewable electricity is an essential prerequisite of cost-competitive green hydrogen production.
- **Political challenges.**
  Conducive and internationally competitive policy contexts will be a foundation for electrolyser development and deployment. Countries like the USA are leading the way in support for green hydrogen technologies through initiatives like the Inflation Reduction Act (IRA), which provides tax credits for green hydrogen producers.
- **Infrastructure challenges.**
  Successful and rapid deployment of electrolyser technologies must be both underpinned and matched by deployment of infrastructure to meet customer needs. This includes the infrastructure required for generation and supply of renewable electricity but also includes hydrogen transport and storage infrastructure. Crucially, the electricity network must be developed to ensure points of renewable electricity generation can be connected to points of storage and use to electricity demand, including green hydrogen production.
- **Supply chain challenges.**
  Some electrolysers rely on valuable and sometimes scarce materials, such as iridium. Securing sustainable supply chains of these components is important, as is R&D to drive innovation to decrease dependency on costly critical elements. Supply chain challenges may also be mitigated by identifying methods to build circular or sustainable end-of-life models for re-use of rare materials (to reduce extraction), which will help secure their supply and retain them at their highest value use within the economy.

Although the electrolysis of water to produce hydrogen and oxygen is a well-defined process, the application of this can vary. There are several types of electrolysers in use or development, each with their own advantage and drawbacks.

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[15] Clean Air Task Force. 2023. Hydrogen Production via Electrolysis. See https://www.catf.us/resource/hydrogen-production-via-electrolysis/ (accessed 5 July 2024).

Alkaline water electrolysis (AWE)

Alkaline electrolysers comprise electrodes separated by a microporous membrane and submerged in an alkaline solution. This alkaline solution is typically made of sodium and potassium hydroxides. The electrodes are usually made of nickel and can be coated with platinum group metals to increase performance and reduce costs Typically these alkaline electrolysers operate at temperatures ranging between 50 – 90 °C and have an efficiency ranging between 62–82% higher heating value[16, 17]. Alkaline electrolysers are technologically mature and are the most widely deployed electrolysers. However, high capital costs coupled with high electricity costs can pose a challenge to their uptake.

Proton Exchange Membrane (PEM) electrolysers

PEM electrolysers utilise membranes which act as both an electrolyte and gas separators. They offer distinct advantages in that they are compact, can be run at relatively low temperatures and, crucially, can be ramped up and down to respond to fluctuating supply and demand within seconds, making them a versatile technology. Their acidic nature means they rely on high quality electrocatalysts and components to ensure running reliability. In terms of electrocatalysts, PEM often rely on precious metals (platinum, iridium, ruthenium) and high purity water. The reliance on such materials may make PEM particularly susceptible to supply-chain challenges.

Solid Oxide Electrolyser Cells (SOECs)

SOECs utilise solid oxide or ceramic electrolysis to produce hydrogen and oxygen. The SOEC process operates at a higher temperature of 500–850°C. SOECs systems have higher efficiency then other systems and could be run in an industrial setting utilising excess heat or steam[18]. SOECs typically utilise yttria-stabilized zirconia as the electrolyte and are not as reliant on rare and expensive materials[19]. One drawback of SOEC systems is that they currently have a shorter lifespan compared to other systems[20]. Currently research and development are focussed on improving running reliability and lifespan of SOEC systems.

Anion Exchange Membrane (AEM) Electrolysers

AEM electrolysers use polymeric anion exchange membranes to split water into hydrogen and oxygen, like PEM systems, however they do this while maintaining an alkaline environment like AWE systems. AEM electrolysers do not heavily rely on rare materials and, due to the alkaline environment, the corrosion rate of materials is lower than other systems. AEMs are at a lower Technology Readiness Level (TRL) and face challenges associated with membrane conductivity, scale up, stability, and, like other electrolyser types, the development of efficient catalysts.

Each electrolyser technology offers distinct benefits and trade-offs depending upon application and may be best used in conjunction according to their strengths.

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[16] Brauns and Turek. 2020. Alkaline water electrolysis powered by renewable energy: a review. *Processes* 8.2: 248.

[17] Tüysüz, H. 2024. Alkaline Water Electrolysis for Green Hydrogen Production. *Accounts of Chemical Research*, 697-710.

[18] Grigoriev, S, Fateev, N, and Millet, P. 2022. Alkaline Electrolysers, in Letcher, T, (ed). *Comprehensive Renewable Energy, Vol 4 (2nd edition).* Elsevier.

[19] Wang, T, Cao, X, Jiao, L. 2022. PEM water electrolysis for hydrogen production: fundamentals, advances, and prospects. *Carbon Neutrality* 1, 21.

[20] The Institute for sustainable process technology. Next Level Solid Oxide Electrolysis. See https://ispt.eu/media/20230508-FINAL-SOE-public-report-ISPT.pdf (accessed 5 July 2024).

2.2. Challenges and interdependencies

Investment and economic challenges

High capital and operating costs will pose a significant challenge to electrolyser uptake. Attracting investment will require greater certainty over costs, as well as supportive policy frameworks that can provide clear signals to investors of a secure and growing industry. Additionality should be a central tenet of green hydrogen development and integration, with hydrogen and associated renewables contributing to a meaningful reduction in emissions and directly replacing fossil-fuel driven processes. Developing a competitive and innovative UK green hydrogen industry can be bolstered by strategic policies and incentives, assisting in overcoming uncertainty among off-takers and promoting international competitiveness.

Supply Chain and Resource Availability

A notable concern associated with some electrolyser technologies is the cost, environmental, social, and economic impacts of the extraction and processing of resources and materials. The dependency for some electrolyser technologies on rare metals, such as iridium, presents a critical risk to the scalability and sustainability of green hydrogen production. Addressing this challenge requires a multifaceted approach, including the application of life cycle analysis, the development of a circular economy in these materials (reducing primary demand for the materials over time), the exploration of alternative materials and, where demand cannot be reduced, diversification and resilience of supply chains.

Scarcity of clean water, used as inputs for most electrolysers, may emerge as a critical resource constraint in the coming years and decades[21]. This could be further exacerbated by changing rainfall patterns with climate change. It may become critical to develop robust water-management systems to ensure proportionate quantity and quality of water supplies are distributed equitably across sectors.

Fluoropolymers are a key component in PEM and AEM electrolysers, but they may be banned in the EU. If exemptions for electrolysers and hydrogen fuel cells are not agreed, then research into suitable alternatives will be needed to alleviate constraints on hydrogen production.

Political and Regulatory Environment

The UK's green hydrogen sector will be influenced by the political and regulatory landscape. Supportive policies which offer clarity and certainty into the long-term will be critical in helping the nascent hydrogen economy develop. Supporting and fostering small companies based in the UK will help hydrogen development, alongside support for larger organisations. Identification of approaches and systems to enable scale up of lower TRL electrolysers and production technologies, as well as research undertaken prior to standardisation, will be of paramount importance. Delays or uncertainties in these areas not only hinder investment but also risk the UK's position in the rapidly evolving global hydrogen economy.

Technological and Operational Improvements

Continued R&D will be essential to overcome the technological and operational challenges faced by current electrolyser technologies. This includes (for the different technologies):

- improving the efficiency, durability, and resistance to degradation of membranes and electrocatalysts;
- reducing the reliance on rare materials;
- reducing the requirement for high-quality water;
- development of large-scale manufacturing processes to drive down costs and mitigate supply chain concerns;
- establishing robust evidence-based quality and assurance (Q&A) and testing standards and the inspection technologies needed to support this;
- reducing technical challenges like gas crossover and water bubbling;
- understanding how electrolysers can be used dynamically and at high currents; and
- improving the efficiency and durability of electrolyser systems.

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[21] Climate Change Committee. 2021. Independent Assessment of UK Climate Risk. See https://www.theccc.org.uk/publication/independent-assessment-of-uk-climate-risk/ (accessed 5 July 2024).

Skills and collaboration

The development of a skilled workforce is critical to the advancement of green hydrogen technologies, underpinning their R&D, product development, manufacture, safe operation, testing, and eventual decommissioning. Regulatory clarity will help inform the skills needed to grow and operate hydrogen technologies but bridging the existing skills gap will also require targeted educational and training programs, enhancing STEM education, as well as initiatives to promote collaboration between industry and academia and continued support in the higher education sector. Collaboration between industry and academia is not only useful for workforce development, but also for fostering innovation. Such mechanisms include use of public-private partnerships, support for university-based SMEs, and development of education programmes in collaboration with industry.

System integration

Each electrolyser type offers specific strengths, and there is an opportunity for optimal balancing of electrolyser technologies according to their strengths and TRL when they are needed. SOECs can be situated competitively in hard-to-decarbonise heat intensive industries, alkaline electrolysers can provide baseload electrolysis, PEMs can be operated variably to account for fluctuations in wind and solar energy supply, and AEMs can overcome challenges associated with supply of purified water and precious metals.

Integrating green hydrogen production into the wider energy system therefore presents both a challenge and an opportunity. For example, on the one hand, there is the challenge of increased demand for renewable electricity to satisfy electrolyser demand but, on the other, there is the opportunity of flexibility in electrolyser demand thereby better enabling more renewable electricity generation (ie the electricity system can cope with high wind generation at times, if electrolyser demand can increase to match that abundance). There is also opportunity to optimise the use of waste heat from industrial processes, to support electrolyser operating temperatures. The location of electrolysers should therefore consider the geography of the future system (ie where other assets will be, such as locations of demand, water supply, subsurface storage, and renewable electricity). Considerations of geography / spatiality should also consider the strengths of different electrolyser types, for instance those which can harness waste heat from industry.

To address challenges, and maximise opportunities, the whole energy system must be considered. Addressing system integration and optimisation holistically can improve the efficiency and economic viability of green hydrogen as a cornerstone of a sustainable energy future.

2.3. Findings

The potential for diverse electrolyser technologies to contribute significantly to the UK's hydrogen production is substantial. However, realising this potential hinges on overcoming a number of salient and related challenges. These range from economic and investment barriers to technological and regulatory hurdles. The path forward requires a concerted effort from all stakeholders involved—policymakers, industry leaders, researchers, and educators – to foster an environment conducive to innovation, investment, and sustainable growth in the green hydrogen sector. Such collaboration can accelerate the development of green hydrogen as a key component of a sustainable and resilient energy system.

- The scale up of green hydrogen is inextricably linked to the scale up, availability of and timely connection to the renewable electricity upon which its production depends as well as, where needed, hydrogen storage and transport infrastructure.
- There is a need to continue to improve the performance of electrolysers, especially with regard to overcoming some common challenges.
- There is no one-size-fits-all electrolyser type, each has different strengths in different contexts. For example. alkaline electrolysers could be used as a baseload, PEM to operate dynamically, and SOECs in clusters with abundant waste heat.
- Approaches and systems to scale-up low TRL electrolysers can help build green hydrogen production capacity and disruptive green businesses.
- Availability of supply chains, especially for raw materials and highly active catalysts, will need to be ensured to avoid bottlenecks.
- Electrolysers may increase competition for high-quality water, which may become increasingly scarce with climate change. Increased desalinisation may overcome potential under-supply of clean water. Even with desalinisation, water costs are likely to remain a small percentage of total cost of hydrogen (<2%), with electricity provision remaining the largest driver of cost.

3. Transporting and storing hydrogen

This chapter explores the technical and operational challenges around the storage and distribution of hydrogen within the UK, primarily focussing on hydrogen in gaseous and liquid form. It can also be stored chemically in liquid organic hydrogen carriers (LOHCs) or ammonia. Ammonia has a higher volumetric energy density than hydrogen and becomes liquid at -33°C, making it easier to store and transport. However, producing ammonia is more expensive than producing hydrogen[22]. Such storage methods also require regeneration / recovery stages which impact the overall efficiency.

Most significant among the key enablers for effective hydrogen transport and storage (T&S) is the establishment of safe, long-term T&S infrastructure, and the strategic spatial design of the hydrogen system.

3.1. Storage media

Hydrogen is challenging to store and transport, having both a low density and a low boiling point (-252.8°C). It is typically stored as a high-pressure gas or a liquid. Liquid hydrogen is less dense than water and must be kept at very low temperatures to avoid boil-off, making it relatively inefficient to store. As a gas, it must be kept under high pressure, depending on storage, from 3 MPa in many industrial settings to approximately 70 MPa in car cylinders. Hydrogen is non-toxic but has a wide flammable range and is a potent indirect greenhouse gas, meaning safety and leak avoidance are essential (see chapter 6). Hydrogen is well known to interact with certain containment materials (for instance, some metals are weakened by 'hydrogen embrittlement'), and further research is needed to fully understand these interactions in certain applications such as aerospace. The optimal storage solutions will ultimately depend on the end-use of the hydrogen and the space available. Understanding the suitability of different storage methods in different locations and applications will help guide the storage requirements of the UK.

Whether stored as a compressed gas or as a liquid, hydrogen transmission and storage infrastructure must ensure leaks are avoided. Current loss rates are estimated to be significant, at 1 – 4% for compressed hydrogen and 10 – 20% for liquefied hydrogen[23].

3.2. Subsurface storage

The use of underground salt caverns is a proven method of long-term hydrogen storage. This storage method allows for inter-year storage, offering the potential to mitigate the impacts of shortfalls in renewable energy generation. Although this storage method is effective, it comes with several uncertainties. One key uncertainty is the environmental impact of the waste brine produced in the excavation of the caverns. As water is used to excavate the salt caverns the waste brine from these sites could have significant impact on local terrestrial and aquatic environments. A possible solution could be to design systems with a view to industrial symbiosis, capturing the brine waste and using it commercially in industries. Another consideration is that the salt caverns must be supplied with a minimum gas supply of 10 – 20% total cavern volume to maintain structural integrity.

3.3. Above surface storage

Hydrogen can be stored above ground in various forms of tanks and cylinders. Storage as a liquid requires very low temperatures in cryogenic tanks making it expensive. Solid state storage (eg metal hydrides) requires high-purity hydrogen, and high-pressure gas storage requires robust physical containment. These forms of storage have considerable energy requirements, estimated to account for up to 10% of stored energy. Some storage technologies are also used to transport hydrogen. These include the use of tube trailers (for hydrogen in a gaseous form) or tankers (liquid).

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[22] The Royal Society. 2020. Ammonia: zero-carbon fertiliser, fuel and energy store. See https://royalsociety.org/news-resources/projects/low-carbon-energy-programme/green-ammonia/ (accessed 20 August 2024)

[23] European Commission. 2022. Hydrogen emissions from a hydrogen economy and their potential global warming impact. See https://publications.jrc.ec.europa.eu/repository/handle/JRC130362 (accessed 5 July 2024).

3.4. Hydrogen transport in the gas grid

The fact that much of the gas network is being upgraded to plastic piping (75% at the time of writing, and an expected 95% by 2032), which is resistant to hydrogen embrittlement, creates the possibility of integrating hydrogen into the existing gas network. Currently, hydrogen can be blended into the gas network up to 20% of the total without the need for upgrades to end-use appliances, but beyond this, appliances must be upgraded.

Line packing hydrogen, in which hydrogen is stored in pipelines in the grid before use, could unlock substantial additional storage capacities, and would also help to provide certainty around demand.

Currently the HI-ACT project is working to establish point-to-point pipelines suitable for hydrogen transport and storage. There are also a range of other ongoing work to identify and establish hydrogen infrastructure including, for instance: the UK Hydrogen Backbone, which aims to join up industrial clusters; HyNet, focussed on hydrogen value chain creation in the North West and North Wales; East Coast Hydrogen, which brings together National Gas, Northern Gas Networks and Cadent to connect planned hydrogen production and storage sites with industrial users, among many other initiatives. However, pipelines and connections between producers and users are most viable if there are multiple off-takers in an area. There is a risk of lock-in if local point-to-point infrastructure is developed with only a few end users, resulting in many single-owner pipelines if mechanisms for opening these up subsequently are not planned for ahead of time.

The continuation of pipeline upgrades to heat-fused plastic piping would help reduce the risk of leaks, but continuous monitoring would still be required.

Gas Networks are already assessing repurposing pipelines to carry hydrogen. It will be important to ensure the suitability of the gas network to hold pressurised hydrogen without becoming structurally unstable, as well as working to understand and avoid leakage, hydrogen embrittlement and potential hydrogen contamination. Depending on usage, contaminated hydrogen may require additional purification steps.

3.5. Strategic planning

As stated, effective transport and storage are critical enablers for the wider deployment of hydrogen technologies. Demonstrator projects can provide insight into the implementation of hydrogen in the UK. However, these projects and further R&D are being constrained due to limited hydrogen availability caused by transport and storage issues. Establishment of trading platforms that collate and match resource availability with user needs could help provide clarity on what resources are needed where and drive a quicker and more efficient identification of opportunities to scale production and use. Questions surrounding how best to bulk store hydrogen in urban areas or ports require investigation.

The evolution of relative costs and delivery costs of each mode of transport will be a critical determinant in the economics of hydrogen.

The spatiality of the future hydrogen system is a central strategic planning consideration. Optimally locating renewable electricity generation, green hydrogen production, and industrial end use marks a key challenge for industrial decarbonisation (see chapter 5). There is also the question of how to transport energy: would turning hydrogen to power and transporting it along electrical lines be optimal, or would hydrogen pipelines be more suitable? Creating a vision for the future hydrogen system will be essential in guiding these decisions.

It is estimated that the hydrogen system required to reach net zero may be of the same scale as the current electricity system by 2050[24] but a first step is to understand the local and regional needs and realities across the UK. Regional plans can outline what T&S structures are needed in different geographies.

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[24] HM Government. 2023. Hydrogen Net Zero Investment Roadmap.

These regional plans could usefully sit within a wider systems-view towards establishing T&S infrastructure. It can be seen that such decisions are starting to be made. For instance, the HyNET project will carry hydrogen, via 100 miles of pipelines, to salt caverns in Cheshire and to industrial users in the region. Salt caverns will be the most viable means to store hydrogen at scale, as the UK has suitable geology to store enough hydrogen at the level required to meet the UK's expected electricity storage needs as well as possibly to provide hydrogen for other uses. The UK is estimated to need 60 – 100 TWhs of hydrogen storage capacity to meet future energy demand using renewable electricity generation[25]. The creation of salt caverns is possible in several areas including Cheshire, East Yorkshire, and Wessex. However, salt caverns take time to establish, and so hydrogen storage capabilities may fall short of what is needed by 2050 if work does not commence at pace. Planning and collaboration with geologists will be required to ensure safety and reduce potential leaks.

Substantial changes, at scale, and guided by the National Energy System Operator (NESO) may be the most viable way towards achieving the scale the UK needs to meet its net zero obligations. The US Inflation Reduction Act (IRA) is a good example of this, having made progress on strategic planning, with a focus on matching supply, transport, and demand. The IRA requires hubs to act as aggregators for off-takers, which helps coordinate the supply side.

3.6. Findings

An efficient and flexible transport and storage infrastructure will need to be developed to ensure that hydrogen demand can be met as hydrogen uses grow across the country.

- T&S infrastructure will underpin the UK hydrogen economy. Developing, demonstrating and upscaling T&S systems which are safe, can minimise losses, and reduce costs for hydrogen compression and purification will be essential.
- The existing gas network can provide an opportunity for H_2 transport, and possible storage through line packing, but the risks of leaks, embrittlement and contamination need further exploration.
- Multiple media exist for hydrogen storage, with solution-mined salt caverns offering the most viable long-term store.
- Hydrogen is challenging to transport as both a liquid and a gas. Alternative forms such as methanol and ammonia exist and may be viable depending on cost. Further research will be needed to identify optimal transport forms.
- Interaction between hydrogen and materials used to store and transport it need to be fully understood across the energy system to reduce risk of environmental or safety impacts.
- More research is needed on how best to bulk store hydrogen in built-up areas such as urban areas or ports, depending on the spatiality of the hydrogen system and end-uses.
- Compression technologies will need to be better understood and developed.
- Establishment of trading platforms that collate and match resource availability with user needs could help provide clarity on what resources are needed where and drive a quicker and more efficient identification of opportunities to scale production and use.

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[25] Royal Society. 2023. Large-scale electricity storage.

4. Hydrogen use

There are a range of opportunities across industries to use green hydrogen as a decarbonising technology, and it can also be used as an energy vector. Examples include:

- transport fuel – e.g. aviation, marine, lorries etc;
- biorefining;
- producing products such as ammonia and chemical feedstocks;
- water desalination;
- high temperature industries such as cement production and glassware;
- steel production (heat and chemical reduction); and
- providing energy for electricity and heating, including for long-term energy storage.

Well-established processes which are already commonplace users of hydrogen (such as producing ammonia for fertiliser production) are not included here, as the infrastructure and end-use are well-defined and operated at scale. However, it should be noted that green hydrogen may be used to produce green ammonia for new applications such as a maritime fuel.

Hydrogen can be used in a variety of applications within an industry, allowing for diversification of technologies and resources. An example of this is within the transport sector.

Fuel Cells

Hydrogen fuel cell technology uses hydrogen as a fuel to generate electricity. Fuel cells operate at higher efficiencies compared to internal combustion engines (ICEs) while also generating negligible emissions[26]. Fuel cell technology has been used in several applications, including the automotive and maritime industries. Although fuel cell technology is well established it does have several challenges for wider take-up. Fuel cells operate without emissions and are durable, however they are currently not cost effective compared to combustion engines. A significant amount of enabling refuelling infrastructure would also be needed to significantly widen the use of fuel cells operating on hydrogen.

Both fuel cell and ICE technologies can be used in aircraft, however the development of higher temperature polymer fuel cells (HT-PEMFCs) (100–200°C[27]) is required. Such HT-PEMFCs would have benefits for a range of other applications by simplifying cooling requirements and lowering system cost.

Combustion

Hydrogen can also be used to power the ICEs of transport vehicles and mobile machinery. Here, the powertrain is fuelled by gaseous hydrogen instead of fossil fuels, retaining some of the existing infrastructure and supply chains. Hydrogen ICEs are slightly more efficient than gasoline engines[28]. Although the combustion of hydrogen does not produce CO_2, it does produce NOx, which are strong indirect greenhouse gases. NOx emissions can be addressed using secondary treatments however this would likely reduce overall system efficiency[29].

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[26] Alternative Fuels Data Centre. See https://afdc.energy.gov/fuels/hydrogen-benefits (accessed 5 July 2024).

[27] Chandan *et al*. 2013. High temperature (HT) polymer electrolyte membrane fuel cells (PEMFC) – A review. *Journal of Power Sources*, 231, 264 – 278.

[28] Alberto Boretti, Hydrogen internal combustion engines to 2030. *International Journal of Hydrogen Energy,* Volume 45, Issue 43, 2020 ISSN 0360-3199,

[29] Sopp & Sopp. 2015, Hydrogen Fuel Cells vs Hydrogen Combustion Engines. See https://www.soppandsopp.co.uk/news/hydrogen-fuel-cells-vs-hydrogen-combustion-engines (accessed 5 July 2024).

Chemical synthesis

Hydrogen can also be used as a feedstock to produce alternative "drop in" fuels such as e-fuels and biofuels. These synthesised drop-in aviation fuels currently underpin the planned sector journey to 2050. However, the estimated quantities needed for aviation alone are equivalent to current levels of global hydrogen production. Indeed, it is estimated that, by 2050, between 65 (conservative) and 90 million tonnes (realistic, aligned to sector progression) of hydrogen feedstock will be needed globally to decarbonise aviation through a mixture of low-carbon aviation fuel use and some direct utilisation of hydrogen (estimated to be below 10% by 2050). Considering a fuel mix approach where some kerosene will still be included in blends, low-carbon aviation fuels and some direct hydrogen use, the IEA forecasts that 13% of hydrogen production will be needed for aviation related use by 2050.

The widespread use of hydrogen within transport industry poses the opportunity for diverse and complementary technologies but also several overarching challenges. These challenges include but are not limited to accessing suitable testing facilities, developing the skills and supply-chains needed to enable development where needed and, in some cases, a significant alteration to existing infrastructure (both in terms of addressing hydrogen accessibility and end-users).

4.1. Interest, appetite and predictions

Hydrogen is a valuable energy vector, and its integration into various value chains and the energy system more broadly should be an important consideration as the hydrogen economy is developed. Current applications, using grey hydrogen, are mainly in the chemical industry, but many opportunities for use exist in other sectors as outlined above.

The TRL of hydrogen technologies varies greatly, as does their potential scalability. The current policies of establishing hydrogen user clusters provide the opportunity to think holistically on a regional and local scale about cross-sector hydrogen applications, allowing for implementation of suitable distribution and storage infrastructure. More formal collaboration, investment and commitments to roadmap production are being observed outside of the UK. Notably, the several Hydrogen Valley initiatives such as those seen in India and the EU as well as similar Hydrogen Hubs in the USA[30, 31, 32]. Crucially, collaboration between clusters will be central to building momentum and scale-up across the UK. Mechanisms which foster collaboration between clusters should be encouraged.

Some current hydrogen applications are already deemed as cheaper and preferable to their high-carbon equivalent. Furthermore, there is not a comparative capital investment being made into fuel cells as there is into electrolysers. Reversible electrolysers / fuel cells are attracting interest, particularly as they can operate with a variety of fuels. Fuel cells are likely to see applications using synthetic fuels, eg ammonia, as fuel cells, although currently costing more than ICEs for example, are much more efficient.

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[30] European Union. 2023, Towards an EU Roadmap for Hydrogen Valleys. See https://www.clean-hydrogen.europa.eu/media/news/towards-eu-roadmap-hydrogen-valleys-regional-actors-and-their-role-double-number-valleys-2025-and-2023-02-21_en (accessed 5 July 2024).

[31] Government of India. 2023, Guidelines for hydrogen valley innovation cluster. See https://dst.gov.in/sites/default/files/Guidelines%20for%20Hydrogen%20Valley%20Innocation%20Cluster_0.pdf (accessed 5 July 2024).

[32] US Dept for Energy. 2024, Regional Clean Hydrogen Hubs. See https://www.energy.gov/oced/regional-clean-hydrogen-hubs-0 (accessed 5 July 2024).

4.2. Future research and unknowns

While hydrogen can be used in a variety of applications and industries, there are several common challenges and barriers to its application as outlined below.

Testing

While the opportunities presented by hydrogen technologies are significant, much research and development is needed at pace to transition to a decarbonised hydrogen economy. This includes providing suitable testing and evaluation facilities for many applications. This may take the form of specialised test centres. For example, in aviation, a national testing centre would be instrumental in not only testing and optimising aircraft technologies (notably the fuel system) but also safety testing, refuelling network testing and life cycle analysis from a holistic environmental perspective.

Testing centres will have limitations and will only be able to demonstrate technologies, and their integration within industrial ecosystems, up to a certain scale. Support and funding schemes that enable industry stakeholders to integrate and trial new technologies, or test their integration with other plant and operations, at scale will be needed.

Another immediate challenge linked to testing is access to hydrogen, which, if not available in the UK would, either force importation of the fuel or the testing of the application overseas, with associated cost and learning limitations.

Materials and critical resources

Future research and development should also focus on the use, testing and reduction in the use of critical resources and materials in hydrogen applications. This includes reducing use of critical resources, like rare earth metals, as well as validating new metallics and composites for use in a hydrogen environment.

Strategies for addressing the availability and use of critical materials need to cover both strategies for ensuring their supply but also strategies for limiting demand. Demand reduction can be achieved through a combination of:

I upstream policy decisions, that account for how policy and technology decisions affect downstream demand for critical materials;

II engineering research, innovation, and design, including materials substitution, where possible, design to minimise critical materials use and to enable ease of recovery and reuse at end-of-life; and

III better recovery, reuse, remanufacturing, and recycling. Critical resource availability and management ultimately requires a cross-sector international approach most notably as demand for a small number of scarce, finite resources is growing.

For example, strategies for water management across various scales (industrially, cross-sectorally, locally, regionally, nationally, and potentially internationally) should be considered due to the high-water consumption of hydrogen production technologies. Availability and ability to recycle high-cost catalysts such as platinum are crucial, not only to reduce the end-user cost of hydrogen technologies, but also to reduce the environmental impact of emerging technologies, encouraging movement towards circular business models. It should be noted that the introduction of fuel cells could reduce the demand for other rare materials used in other technologies, for example replacing Li-ion batteries.

4.3. Wider barriers to scaling up hydrogen use

Skills

The transition to a decarbonised economy will have a direct impact on the UK and global skills markets. It is therefore imperative to incentivise industry reskilling and encourage skills development from apprenticeships up to post-graduates, including into the supply chain. Collaboration between industry and academia can enable reskilling and upskilling both for industrial and academic workforces, to cover both short-term market-ready technologies and to develop emerging long-term technologies.

Frameworks and strategies

Clear government strategies, delivery plans and market incentives are needed, not only for new technology innovation, but also for investment to scale up market-ready technologies and integrating them into industrial ecosystems.

International and cross-sectoral collaboration could aid scale-up and should be underpinned by establishing common standards and technologies. An example of this is the need for a revised Jet Zero strategy that is more ambitious and provides short- and long-term actions, drives business incentives and supports international technology and infrastructure transitions. Similarly, calls for industrial-cluster-level, local, regional, and national industrial and transport networks require effective coordination of sector ambitions, skills, resources, and logistics over the short- and long-term.

The UK could play a leading role in establishing internationally recognised hydrogen standards. Building such international frameworks and technological standards for hydrogen use would help pave the way for hydrogen trade opportunities, in which the UK, were it to move at pace, could become an exporter of hydrogen technology.

Pace

The increasing interest in the applications of hydrogen poses both a strong international opportunity for the UK, but also a threat and means that movement at pace is required. Learning and adopting lessons from past examples of rapid roll-out, such as the development of offshore wind, can accelerate the pace of development and rollout of hydrogen and assisting technologies. Pioneering emerging technologies provides the opportunity for the UK to assume a global leadership position on hydrogen technology innovation, if strong funding commitments and decisive action are taken now to scaling up current technologies, which have reached technological maturity, but which now need support to reach commercial maturity at pace.

One should not underestimate the possible long-term impact of having to test and operate overseas on the prospects for the UK to exploit the long-term industrial green hydrogen opportunity. Countries such as the USA and Germany are better equipped than the UK in terms of hydrogen test facilities and associated early supply chain. Further, UK leadership in some technologies eg fuel system or wings in aerospace might be lost if hydrogen technologies in aerospace are moved offshore.

4.4. Findings

While green hydrogen poses opportunities for use in a wide variety of decarbonised and decarbonising technologies, it is apparent that there is a range of considerations which require clear consideration, analysis, and strategy. The need to develop assisting regulatory and policy frameworks to alleviate not only uncertainty in off-takers, but also to ensure production is in step with other regulators and industries is crucial. It is also clear that greater testing facilities and technology optimisation and development are needed to optimise and better understand the switch to a decarbonised economy in UK industry.

- Pace of development is essential for rapid deployment and use of hydrogen technologies and infrastructure, in order help the UK progress towards net zero and establish itself as a leading nation in hydrogen use, enabled by a strong indigenous supply chain.
- Hydrogen is a promising option in the long-term for decarbonising aviation, but it is also essential for bio and electro fuels in the near to mid-term and ought to be part of a no-regret solution.
- Fuel cells are efficient and produce negligible emissions and may be applied across a range of transport systems and in back-up power systems.
- Hydrogen ICE's can deliver climate mitigation and air quality improvements and are compatible with existing manufacturing processes. They may play a role in HGVs and construction equipment. They are currently less efficient than fuel-cells, and battery-powered EVs.
- The TRL of hydrogen technologies varies. Collaboration between clusters, and between industries, can aid development and scale-up.
- There is a need for greater R&D and testing across hydrogen uses.
- Promoting recycling and efficient use of materials can help overcome sustainability challenges associated with hydrogen production and use.
- Regulatory frameworks could help support the integration of hydrogen technologies into existing markets and infrastructures.

5. Whole energy systems approach

Addressing complex challenges like reaching net zero requires consideration of the entire energy landscape, enabling and optimising clean and long-lasting solutions. A systems view allows for a comprehensive understanding of how changes in one part of the overall system affect others, and how parts of the system mutually interact, paving the way for a more adaptable and resilient energy landscape and avoiding unintended consequences.

5.1. Challenges requiring systems level solutions

There are a number of barriers and challenges for which system-level thinking will be required to deliver optimal outcomes. For instance, the development of the UK hydrogen economy will be a national, regional and local endeavour. However, initial investments required for hydrogen may be locally prohibitive and local authorities might lack the skills and budgets required to properly conduct Local Area Energy Planning and the cross-sector convening and coordination that is required. Against other competing priorities, hydrogen, and other net zero initiatives are often not prioritised. National scale action may therefore be required to fund and co-ordinate development of hydrogen systems, and there will be a need for greater cooperation between local authorities and national government on strategic planning and decision making.

Collaboration and knowledge sharing between clusters, rather than competition, should also be fostered to aid development and scale-up of hydrogen technologies and uses, through, for example, the use of funding regimes. Crucially, the energy system (and the models used to underpin it) must be sensitive to local realities and needs. As the hydrogen economy develops, resource constraints may emerge in some areas, for instance around the availability of purified water for hydrogen production (something that may change with climate change). Working to identify possible future constraints at the local and regional scale could help inform planning decisions at the national scale.

National level barriers include the difficulty of integrating diverse regional approaches into a unified national strategy, as well as political uncertainty. Investor concerns about stranded assets and a lack of certainty can further compound national challenges. There is a need for infrastructure investment and strategic planning to support the hydrogen transition across the production, storage, transportation, and end use sectors, alongside the development of a skilled workforce.

Climate change itself poses a threat to the future resilience of the UK energy system. System resilience at the national scale will need to be accounted for, and the future development of water, electricity, and hydrogen systems will need to be managed to ensure this resilience.

There are many salient challenges at the international scale, primarily related to global supply chains and international competition. The trade of hydrogen and associated technologies for supply chains may be susceptible to globally disruptive shocks, which can undermine progress in establishing hydrogen systems and technologies. This could be overcome by development of domestic manufacturing. There may be skills shortages as well as flows of skills across borders, and therefore developing and retaining UK skills should be a key goal. International hydrogen investment by competitor nations and large global corporations is significantly greater than investment by the UK Government, across R&D, product development and manufacturing. Development of capability in hydrogen at scale requires large-scale investment.

5.2. Modelling the energy system to inform local, regional and national planning

Models can play a role in informing strategic decision making in complex and interconnected systems. Modelling hydrogen's role within the energy system is complex. Existing energy models often, by necessity, exclude factors beyond engineering challenges (consumer behaviour, for instance), often adopting a business-as-usual approach to certain sectors, such as automotive, and are limited by their assumptions, which can be opaque. Models should envision different market futures influenced and shaped by intervention, recognising the economic significance and the environmental impact of different options.

A focus on whole-system modelling can help aid long-term planning, short-term operations, and prioritisation by enabling a focus on the relationships between component parts of the system (the system dynamics). Whole-system modelling could consider factors beyond cost optimisation and infrastructure challenges, including environmental implications, energy security and reliability, limitations on the speed of scale up (such as factory build time, training, and regulations), and the effects of wider domestic and international economic contexts and developments (such as the availability of imports). Research gaps, including the need for high-resolution models and integrating social science (for instance, accounting for stakeholder decision making processes), will continue to pose challenges to detailed system models. Further research gaps can be addressed by:

- refining or improving the temporal and spatial resolutions used, eg using agent-based modelling to better understand market, stakeholder and consumer behaviour and preferences;
- integrating agent-based modelling into broader system models to better understand how behaviours may impact system dynamics; and
- quantifying the whole-system flexibility offered by hydrogen as well as its net benefits.

No model can consider every variable, but these specific research gaps are a significant hindrance to whole system analysis and understanding.

5.3. Opportunities

Local opportunities can be unlocked by leveraging the unique strengths of specific industries, sectors or regions through Local Area Energy Plans (LAEP). Establishing clarity on opportunities (including identifying demand and matching it with opportunities for supply) and the challenges to be addressed at the local scale, which will differ between LAs, will be an essential process. Collaboration with local authorities, co-ordinated by NESO and aligned with the national hydrogen development goals and LAEPs, will therefore be essential to building a hydrogen economy at pace.

Understanding and modelling local energy systems and integrating this into wider models can aid exploration of optimisation strategies for hydrogen production and use across scales. As well as feeding into and informing LAEP processes, local models could usefully integrate power, water, hydrogen and district heating systems (for example) into a central model. The development of the Strategic Spatial Energy Plan[33] as recommended by the UK's National Electricity Network's Commissioner and being taken forward by the National Energy System Operator (NESO) is a positive step forwards in connecting government policy and infrastructure development plans to aid in scoping optimal locations for energy infrastructure, nationally and locally.

Depending on the placement of electrolysers, there are opportunities for local-scale production of green hydrogen when local weather means surplus generation of renewable energy. Smart hydrogen systems and energy grids could underpin this system, working in unison to provide real-time information on green electricity for immediate distribution and consumption as well as electricity available for hydrogen production. To realise these opportunities, Local area energy planning would be most effective when aligned with national strategies.

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[33] UK Government. 2023, Electricity networks: transmission acceleration action plan. See https://www.gov.uk/government/publications/electricity-networks-transmission-acceleration-action-plan (accessed 5 July 2023).

National opportunities and regional benefits need to be aligned. Identifying and prioritising low-regret actions is critical and will help inform strategic decision-making. Doing so will help avoid hesitancy over what may constitute the final end-use cases for hydrogen in the future up to 2050, and subsequent inertia in the development of the technologies needed now to catalyse growth in hydrogen production and use. There is an opportunity for comprehensive modelling of the energy system to understand the opportunities and impacts of hydrogen over the coming decades and for AI and digital twins to underpin smart systems and more fully outline the optimal pathway to national and regional scale integration of energy systems.

At the international scale, the UK has the potential to learn from global hydrogen roadmaps and the models of other countries. At the time of writing, 53 national hydrogen roadmaps exist. The UK has modelling and R&D strengths which can be leveraged to help the UK attract investment.

Opportunities to export hydrogen and hydrogen-related technologies will also arise, provided a strong UK hydrogen sector and identification of optimal international markets and transport media. Hydrogen exports, as well as international trade in technologies and resources across the hydrogen value chain, will rely on international cooperation on standardising hydrogen quality metrics, technology testing standards, and regulation.

5.4. Findings

It is critical that the role and operation of a UK hydrogen economy is considered in the broader context of the UK energy and resources systems.

- Scale, geography, and existing and foreseen infrastructure will be key considerations in hydrogen system planning. The system should be designed with future uses and longevity in mind.
- Infrastructure will be a limiting factor if it does not match the pace of development of other technologies. For instance, slow development of storage infrastructure will in turn delay upstream and downstream infrastructure and uses.
- Co-location can reduce the need for hydrogen transport infrastructure, and present opportunities for re-use of industrial waste heat for hydrogen production. Place-based innovation clusters can form the bedrock for future innovation and end-uses.
- A focus on system wide opportunities and efficiency of green hydrogen should be at the heart of planning, and there is a need for whole-system optimisation, industrial symbiosis.
- Factory and infrastructure building time, as well as speed of manufacturing of materials, can delay projects, and should be considered in system modelling and planning.
- The future hydrogen system will need to be resilient to increasing climate risks.
- Local opportunities can be unlocked by leveraging the unique strengths of specific industries, sectors, or regions through Local Area Energy Plans, however local authorities can lack the skills and budgets required to properly conduct Local Area Energy Planning and the cross-sector convening and coordination that is required.
- Advanced models at the system scale, which take into account novel variables such as stakeholder behaviour and decision making, can help inform the decisions and planning processes necessary to meet the above.
- Significant investment is needed to develop a domestic hydrogen supply chain if the UK is to maximise the benefit of current leadership in R&D and compete on the global scale.

6. Safety and environmental Impact

The transition towards a hydrogen economy will bring with it critical new considerations around safety and environmental hazards. This chapter explores the challenges and how to overcome them on the UK's journey towards delivering a hydrogen economy.

6.1. Hydrogen safety

Globally, 100 million tonnes of hydrogen are produced and consumed safely in industrial contexts each year, and safe practice and regulations for large scale use are well developed[34]. New applications such as hydrogen for domestic heating or passenger vehicles would inevitably bring hydrogen closer to untrained consumers making the need to establish safe practices a priority.

The physical properties of hydrogen make it a challenging element to work with, due to its wide flammable range, difficulty in detection, and leakage potential. However, with proper handling, it can be used safely. Establishing the systems to use hydrogen both safely and effectively in different contexts is essential. A majority (75%) of hydrogen related accidents in the recent past are a result of the errors in operational systems, with 35% of accidents resulting in explosions and 24% in fires[35]. These incidents typically arise from multiple failures within a system, including management failures alongside system design or human errors. Hydrogen is already used widely in industry today, and hydrogen for domestic use has a precedent: hydrogen was a major component of coal gas ('town gas') piped to homes in the UK before natural gas became available in the 1970s.

While highly flammable, hydrogen is non-toxic and, if gaseous hydrogen is accidentally released into the atmosphere, it can rise and disperse quickly. There are potentially higher risks associated with the accidental release of cryogenic liquid hydrogen where pooling at ground level is possible. As liquid hydrogen evaporates with a volume expansion of 1:848, it does pose significant risk as a highly flammable gas. Oxygen enriched air further increases the combustion rate of flammable and combustible materials, including clothing.

The most pressing challenge is to educate potential users of hydrogen about the risks and develop new safety, testing, and maintenance protocols. A robust regulatory framework, enforcement, standardisation of safety requirements, enhanced national and international collaboration for knowledge sharing, and fostering a culture of hydrogen safety in industry is essential.

6.2. Environmental impacts

Hydrogen is an indirect greenhouse gas. It oxidizes hydroxyl radicals in the troposphere which in turn prolongs the life of methane and increases production of tropospheric ozone and stratospheric water vapour, each of which are potent greenhouse gases. Current loss rates are estimated to be significant, at 1 – 4% for compressed hydrogen and 10 – 20% for liquefied hydrogen[36]. Hydrogen is a small molecule and is therefore more likely to leak than natural gas, making leak detection and monitoring systems essential. It is therefore essential to plan for and implement regular monitoring and maintenance works for any future network.

Work must be undertaken to minimise leaks, supported by domestic and international standards. Preventing leaks and incidents across hydrogen production, transport, storage, and use will be essential to avoid the UK hydrogen system contributing to emissions.

Environmental concerns also extend to the significant water demand of green hydrogen production processes, the materials required within production technologies (and related impacts in extracting and processing them), and the potential biohazard from atmospheric hydrogen concentrations including through enhancing microbe growth in confined spaces.

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[34] IEA. 2023. Global Hydrogen Review 2023.

[35] Wen, J, *et al.* 2022. Statistics, lessons learned and recommendations from analysis of HIAD 2.0 database. *Int. J of Hydrogen Energy*, 47 (38).

[36] European Union. 2022, Hydrogen emissions from a hydrogen economy and their potential global warming impact. See https://publications.jrc.ec.europa.eu/repository/handle/JRC130362 (accessed 5 July 2024).

6.3. Minimising risks and impacts

There are a range of solutions to minimise and prevent the impacts of hydrogen upscaling in the UK, resting on regulation, supply chains, skills, innovation, and research. Developing and encouraging regular testing regimes, especially for new technologies, could improve safety and mitigate environmental risks. Similarly, as new entrants to the sector emerge, especially in the short and medium term, ensuring regulations and quality assurance are in place, are fit-for-purpose and adhered to, will further solidify safe operation of hydrogen technologies. This will also need to be underpinned by suitable skills and access to training. This will include ensuring sufficient skills and expertise within the quality assurance regime, eg within testing and certification providers.

6.4. Circularity and life cycle assessment

It will be crucial to develop a circular hydrogen economy to reduce reliance on scarce critical materials and to improve the efficiency of water and energy use across hydrogen production methods. Reducing the need for virgin raw materials will help prevent rising costs driven by scarcity and international competition, as well as reducing the upstream impacts of extraction and processing.

Research will be central to improving the recyclability of key materials, as well as pathways for research to feed into innovation. Research and innovation are also needed to improve the efficiency of key green hydrogen technologies, like electrolysers, to reduce the amount of material needed in their production and maintenance.

Life cycle analysis approaches will also need to be bolstered to inform the impacts and approaches towards circularity of different components within the hydrogen system. This should be supported by LCA skills and knowledge production.

6.5. Regulation and governance

The regulation of hydrogen technologies and applications requires careful consideration to ensure safety and environmental protection, as well as contributing towards industry growth. Uncertainty in regulatory frameworks can deter investment, underscoring the importance of developing clear, informed policies that support the hydrogen economy's evolution. This involves identifying non-negotiable regulatory areas, such as safety and environmental protection, while allowing for innovation and growth within the industry. Regulation will need to be reviewed continually to ensure it can keep pace with innovation.

Additionally, regulation and governance can be instrumental in ensuring the education and knowledge sharing of crucial safety protocols not only among technicians and users, but also among the emergency services.

6.6. Public understanding and engagement

The public perception and understanding of hydrogen vary widely, influenced by historical events and limited exposure to hydrogen technologies. There will be a need to undertake public consultation to understand public concerns around hydrogen, as well as to clarify the role of hydrogen in the UK's future energy mix. Efforts to enhance public engagement should focus on demystifying hydrogen safety and environmental impact through transparent, accessible, and credible information that is focused on how hydrogen systems can be made safe, and to demonstrate trustworthiness. Crucially, demonstration of trustworthiness must be underpinned by listening to and taking seriously public concerns around hydrogen technology.

6.7. Findings

The transition to a hydrogen economy in the UK presents a complex interplay of safety, environmental, and regulatory challenges. Addressing these concerns requires: a multi-faceted approach involving robust and continually updated safety protocols, strategies to better understand and minimise environmental impacts, public engagement efforts, and clear regulatory frameworks. Underpinning these requirements lies the need for collaboration between research institutions, industry, and government, to understand the challenges, identify solutions, and build conducive regulatory and policy landscapes to support the safe and productive use of hydrogen in the UK and to demonstrate trustworthiness to the public.

The increased and wider use of hydrogen will give rise to new safety and environmental risks, however current industrial experience shows that these risks can be managed and mitigated.

- Ensuring a safe, well-regulated hydrogen economy is essential.
- Greater public consultation and communication to understand public concerns around hydrogen storage, transport, and use will be important. Transparency and communication on the safety of hydrogen through reliable and credible sources will be necessary.
- Safety will be underpinned by robust training systems and a highly skilled workforce. This in part depends on excellent UK research infrastructure, collaboration between industry and educational institutions to develop appropriate programmes, appropriate standardisation and regulation, and certification schemes.
- Further research into updated LCA methodologies, and specific technology and application safety risks, will be needed.
- Monitoring along the hydrogen supply chain will be essential to identify and rapidly respond to leaks.

7. Cross-cutting issues

Several common or cross-sectoral issues are clear. These can be broken down into the following categories:

- vision and planning;
- commercialisation;
- skills and competencies;
- regulations and standards;
- resources and infrastructure; and
- risks and public acceptance.

7.1. Vision and planning

Whilst the UK Hydrogen Strategy is a positive indicator of the UK Government's interest and support for Green Hydrogen Production in the UK, the biggest obstacle to many aspects of building an efficient UK green hydrogen economy is the lack of a clear vision and a detailed delivery plan for the UK. Addressing this would provide much greater certainty to investors and drive the incentive to act at pace. An agreed, longer-term vision would bring confidence to investors and companies in the supply chain, drive pace in delivery and give direction to researchers and innovators. Developing this vision in an international context would also be critical, highlighting export potential, resource constraints, competition, and opportunities for international co-operation. A holistic view is required of where manufacturing exists or could be developed, what could only be imported and therefore where critical supporting infrastructure, such as pipelines, will be needed and over what timeframe. The vision and planning needs to concurrently support the scale up and development of hydrogen production and demand, including end use technologies. Demonstration and test sites are needed to determine the most viable technologies in real world settings Crucially, however, scale up needs to not only encompass demonstration, but to bridge the gap between demonstration and pilot-scale projects, and large-scale integration within industrial ecosystems.

Alongside this, greater collaboration and information sharing is needed between academia and industry to develop technologies, enable better public engagement and consultation, build the skills base and encourage investment.

7.2. Commercialisation

In addition to the need for a clear plan, the greatest barriers to many new technologies and hydrogen uses revolve around finance and investment. These relate to the need: to foster reliable demand (and to match production with demand); develop robust and resilient supply chains in a global context; overcome the uncertainty customers might have about a reliable hydrogen supply and reduce delays in building the necessary infrastructure and industry.

Investors highlight three big categories of risks in commercialising hydrogen that apply to all technologies to a greater or lesser extent: commercialisation risks, technological risks, and market risks.

There exists a range of commercialisation risks, which may serve to slow development of the hydrogen economy. This includes the sheer size of projects, combined with the level of new technology, equipment, applications, markets and uses, which can drive uncertainty. The large amount of CAPEX required, as well as the long timescale before first revenue, compounds this challenge.

There also exist technological risks to commercialisation, in that many novel and mature green hydrogen technologies have not yet been used at scale. Attracting investment and upscaling technologies at the level needed to achieve the government's aims requires around a 100-fold increase in capacity in the coming decade, far greater than the usual level of upscaling in other sectors.

Market risks also exist, in which investors and producers face uncertainty that future markets for green hydrogen will exist and be differentiated. Commercialisation at the pace required will be dampened without greater certainty on future markets and end-uses. The government's HAR schemes are a step in the right direction to addressing this challenge.

Delays can result from funding gaps, skills shortages, supply chain hiccups (including the supply of machinery and parts) or missing infrastructure, all of which increase risks and can scare off investors.

Private investment is central to establishing a hydrogen economy, however for technologies to succeed, support is needed to take them from low to high TRL, along with investment in manufacturing capacity. In practice, investment is often difficult to obtain for small companies with low TRL products, as the risks are either too great (at the scales of commitment required) or unclear. The current level of low-TRL funding has unlocked some technologies, but additional funding will be needed, as well as funding for second- and third-of-a-kind technologies which can build on first-of-a-kind funding.

7.3. Skills and competencies

As described earlier, potential shortages of people with the right skills and competencies will hold back research and the development of hydrogen related businesses. The UK has historically strong expertise in the oil and gas sector, as well as engineering, procurement, and construction (EPC) businesses, which may prove highly transferable to the hydrogen economy. Nevertheless, the UK, and indeed the global, hydrogen skills base will need to be grown in both academia and industry if the hydrogen economy is to be sustainable. As with many engineering industries, the current hydrogen industry has an aging workforce and faces competition for new talent from many other new and developing industries. Mapping out the existing skills base and determining the future needs would help direct investment and funding. Skills retention and retraining also need to be addressed, through the development of training facilities, recognised courses, qualifications, and formal competence certification. The Hydrogen Skills Alliance has been established to convene those involved in identifying, articulating, and addressing the skills and workforce needs of industry in relation to the hydrogen economy.

In addition to increasing numbers and raising competence levels, the industry needs to develop mechanisms to share experiences and lessons learned across regions and supply chains. This would help the industry to attract more funding and expand. The reputation (and therefore the trustworthiness to the public of the expansion) of the hydrogen industry will also depend upon avoiding and learning from accidents and incidents.

7.4. Regulations and standards

Changes in energy supply and use need regulation and standards to ensure that the technology operates safely, to the quality required and to enable trade. The technologies for hydrogen production, storage, transportation, and use are no different. Existing regulation for the use of hydrogen in industry is mature, but there may be regulatory gaps depending on how hydrogen will be used in the future. Developing regulation and standards around hydrogen use in non-industrial settings, and for electrolyser technologies, should be a priority. Internationally recognised quality and testing standards and comparative regulations are needed to ensure a level playing field and encourage and support trade in technologies and green hydrogen.

As always, there is a balance to be struck between regulation that ensures safety and promotes competition and that encourages growth and innovation. The necessary infrastructure, personnel and skills for regulations, accreditation and quality assurance will need to be established to ensure compliance and build confidence in the technologies.

The UK has robust land use regulation and often planning is slow and prone to delays, which can disincentivise or delay project development. Such delays may stall the development of production, transport, and storage infrastructure in coming years and may lead to sub-optimal location of infrastructure. Delays may also render some projects unviable as continued technological innovation can lead to a need to re-engineer delayed projects. Crucially, nations which are able to approve and deliver projects more rapidly will likely become a more attractive prospect for hydrogen businesses and further investment and may seek to encourage relocation of hydrogen enterprises and projects through either direct or indirect incentives.

7.5. Market mechanisms

New market mechanisms may need to be deployed to overcome challenges in bringing the future hydrogen economy into fruition. For instance, green hydrogen will, by definition, be closely coupled to the electricity markets, the composition of the grid and access to suitable power generation options. Existing challenges facing renewable energy – for instance, the marginal cost pricing system in which the most expensive energy source drawn upon to produce electricity (often gas) sets the wholesale price of electricity – will in turn influence green hydrogen production costs under current market arrangements. Grid connectivity will present another challenge to renewable electricity and may lead to consider options such as small modular reactors (SMR), linked to feedstock and fuel production.

Secondly, market mechanisms may be needed to support Long Duration Energy Storage (LDES), to incentivise large-scale hydrogen storage development as well as cost-effective operation over long timescales. This could take the form of centrally driven coordination of investment plans, cooperation of members of power pools, or establishment of a central buyer with responsibility for purchasing power from generators and selling it to consumers[37].

7.6. Resources and infrastructure

There are three areas of concern regarding resource constraints: water, renewable electricity, and scarce materials.

Competition for water is already difficult and could become more so with a changing climate and rainfall patterns. The use of sea water and waste industrial water could ease competition for clean water but would require additional water treatment prior to use.

Though the relevant policies for decarbonisation and growth in the electricity system are out of the scope of this report, green hydrogen production is one of many contributors to future growth in demand for renewable electricity and this means that growth in green hydrogen is inextricably linked to the successful delivery of (and subsequent growth in) a decarbonised electricity system.

The dependence on scarce critical materials is detailed in section 4.2. as are the strategies that will be essential to managing this. These lie across both ensuring sustainable supply but also driving reductions in demand for primary resources and the associated environmental and societal impacts of material extraction. Strategies for demand reduction sit across upstream policy and technology decisions, innovation in electrolyser design (including design for materials recovery and reuse) and establishing much greater material recovery and recycling.

The development of hydrogen infrastructure will have a direct bearing on the development of the hydrogen economy. Currently, hydrogen industries are being developed (with a focus on production) in clusters at various points around the country. However, it is likely that hydrogen will be in use across the country and the distribution and storage infrastructure (eg pipelines) need to be planned and installed at a pace to match rising demand and to enable future developments (major hydrogen stores in East Yorkshire or Cheshire, for example). Similarly, R&D infrastructure, including testing and quality assurance facilities will need to be developed and made easily accessible. A central facility to share R&D results, safety and environmental experiences and hydrogen knowledge across the industry is vital.

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[37] Royal Society. 2023. Large-scale electricity storage. See royalsociety.org/electricity-storage (accessed 20 August 2024).

7.7. Risks and public acceptance

Public perception of the risks of using hydrogen more widely in society will be influenced by the impact of accidents and incidents and the industries and government's responses to them. The public's current experience of hydrogen is very narrow and in the main historical. Public trust will depend on effective and honest public consultation and communication of all the risks, benefits, and safeguards, particularly in relation to hydrogen applications that directly involve the public, such as transport. Further social science research is needed to inform the creation of trustworthy hydrogen systems and help address existing and new concerns.

A safe and acceptable hydrogen economy will require a good understanding and mitigation of the risks posed by the production, transport, storage, and use of hydrogen. Safety standards and procedures will need to be developed, along with training and certification of design, maintenance, and operating personnel. Similar to experiences in other sectors, such as the nuclear industry, cross supply chain and inter sector information sharing will be critical to effective reductions of risks and accidents. This would be particularly useful for small companies, who often do not have the depth of expertise or experience of dealing with hydrogen at scale.

No less important is the impact of hydrogen use on the environment and biodiversity. Further research is needed to establish full life cycle analysis (LCA) for green hydrogen production and LCAs and safety analysis for novel hydrogen uses.

The industry must earn public trust and so all safety, environmental and risk information should be openly available through a trusted independent organisation.

7.8. Timeline to achieve a hydrogen economy

The main challenges and actions outlined in the report have been placed on a timeline to achieve net zero by 2050, which can be found in table 1, p 40. For convenience the timeline is set out in 5-year periods from 2025 and many of the actions are included in the next ten years. This reflects the need to progress establishing a hydrogen economy quickly as time to make the necessary carbon impact is short and the opportunity to gaining leadership in the hydrogen production, transport and use technologies is closing.

8. Policy interventions and incentives

The transition to a hydrogen economy in the UK will require strategic policy interventions to address challenges and capitalise on opportunities for investment, innovation and job creation. Policy needs to be oriented toward mechanisms for facilitating capital flow, regional development, and anchoring value from a hydrogen sector in the UK.

8.1. Policy goals

Long term national strategy

The commitment and appetite for hydrogen within HMG has grown considerably and rapidly within the last 5 years. In December 2023, the UK Government committed to £2 billion in funding to support the production of hydrogen[38]. This should be the beginning of a continued process of analysis, review, and support for the scale up of hydrogen technologies and infrastructure in the UK to ensure technologies are developed and scaled-up into the future. Ensuring that policies remain flexible to respond to and accommodate emerging energy solutions without moving too cautiously or slowly will be a balancing act for policymakers.

Despite this, to support delivery of the ambition to develop up to 10GW of low-carbon hydrogen production capacity by 2030, greater clarity of sector specific decarbonisation processes and pathways utilising hydrogen are needed. Government could work closely with industry to advise on achievable decarbonisation pathways. Well-evidenced decarbonisation pathways, which clearly integrate decarbonisation with economic growth opportunities, jobs creation and international challenges and policies to address costs and barriers across sectors would be a significant step in providing the longer-term forward view that investors and businesses need to invest with confidence in projects, skills and supply chains, accelerate scale up and bring down lead times.

Local and regional delivery

Establishing clarity on opportunities (including identifying demand and matching it with opportunities for supply) and the challenges to be addressed at the local scale, which will differ between LAs, will be an essential process. Collaboration with local authorities, co-ordinated by NESO and aligned with the national hydrogen development goals and Local Area Energy Planning, will therefore be essential to building a hydrogen economy at pace.

Manchester stands as an example of a regional model for hydrogen strategy development in partnership across sectors. The Manchester Fuel Cell Innovation Centre, which is based at Manchester Metropolitan University and part of the broader Greater Manchester Strategy for achieving net zero by 2038, was part funded through regional development funding. The Centre was highlighted as successful in fostering co-operation between local authorities on funding and planning. The partnership brings together policy makers, academics, and industry experts and has set up an ecosystem for hydrogen fuel-cell R&D. This includes support for many regional projects, from demand generation through to technical R&D and hydrogen education programmes. The initiative highlights how establishing shared aims on key areas (skills, employment, and investment, for instance) will help guide the direction of travel across local authorities. These successes could be replicated elsewhere, fostering a common vision across local authorities, through consultation and collaboration, generating the levels of ambition, join-up and coordination needed to achieve national green hydrogen development targets. Co-development of policy with academics and local industry will be critical to success. Initiatives such as this should be encouraged and enabled to provide a bottom-up and whole-systems view of the opportunities at local and regional levels and to avoid unintended policy impacts.

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[38] £2bn in revenue support for 15 years (similar approach to a CfD) for the first 125 MW of new electrolytic hydrogen projects. The stated ambition is to have 6 GW of electrolytic by 2030. It is part of a series of funding rounds for hydrogen deployment (production, storage, transportation and also use in the power system). R&I funding is separate as is funding for other use cases beyond power.

Updates to existing regulatory and planning systems may be required to achieve the scale of the green hydrogen capacity needed and at the pace required. For instance, existing planning laws enable large projects to be halted by individual landowners, which can both jeopardise planned projects and reduce appetite to develop future projects in the UK. This may prove to be a significant hindrance and has already had a material impact on planned electrolyser projects, especially as other countries seek to incentivise relocation of hydrogen projects and capital to within their borders. Reforms which protect the rights of landowners and communities while fostering development may prove crucial to delivering green hydrogen capacity at the pace required to meet national targets.

Innovative policies can increase levels of investment, critical at this early stage of the hydrogen economy's development. These could take the shape of specific hydrogen investment zones, similar to existing investment zones[39].

Joined-up support toward but also beyond testing and demonstration

Building investor confidence through consistent messaging and evidence-based strategies is crucial to generating buy-in from a variety of stakeholders. There are concerns that funding is atomised across geographies, competitions and allocation rounds and furthermore, tend not to fund periods in line with the timeframes needed to scale up new facilities and infrastructure. Funding rounds for green hydrogen technologies are most effective if they stretch over many years, like the HAR, as this allows for long lead times for the development of new facilities and what this involves, such as sourcing and installing novel equipment. Continued funding will allow novel technologies to progress towards deployment. However, there is currently limited support to move demonstrated technologies into stable operation and scale-up. Identifying approaches to enable technologies to move beyond demonstration into successful commercial operation will mark an important next step in the development of the UK hydrogen economy.

Long-term consistency and ambition, combined with better local and regional coordination and planning and extended timelines for innovation funding for hydrogen would encourage the inward investment and scale up needed.

8.2. Enabling capital to flow

A barrier to successful roll out of hydrogen technologies is access to funding. Developing a culture that takes a multi-faceted approach to attracting capital to projects will be crucial to success. Investors are not a homogenous group. Each broad type of investor (venture capitalists, private capitalists, private wealth offices, sovereign wealth funds, corporate ventures etc.) have different investment levels, risk appetites, and target TRLs.

Corporate investors, for example, look for:

- long-term assurance for major capital investments;
- investment opportunities in infrastructure that are long-term, extending beyond political cycles and confidence in the conditions for their investment;
- greater market certainty justifying demand and a serendipitous, enabling investment; and
- other often overlooked aspects of the UK investment environment such as university research facilities, infrastructure, specialist knowledge, skills, and Intellectual Property (IP).

In contrast, for example, for venture capital, the biggest challenge is identifying high quality companies to invest in. Investors currently undertake the time-consuming task of assessing a large number of approaches (eg a company's leadership, business model, financials etc). A quality assurance, or kite mark, system to give confidence to investors[40] would help to overcome this.

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[39] UK Government. 2023, Investment Zones: technical document. See https://www.gov.uk/government/publications/investment-zones-technical-document/investment-zones-technical-document (accessed 5 July 2024).

[40] For example, the Shott Scale UP Accelerator Programme from the Royal Academy of Engineering's Enterprise Hub and the TechX Accelerator from the Net Zero Technology Centre as successful examples of this.

The UK policy landscape plays a crucial role in galvanising the funding ecosystem and can bolster future funding in UK hydrogen projects. Two key approaches UK Government can take to enable capital flows are:

1. Providing confidence and assurance for major capital investment opportunities in infrastructure which is long-term and extends beyond political cycles. Messaging and scrutiny from the Treasury are considered as essential, and the department could usefully undertake a cost-benefit analysis into hydrogen technology which may serve to foster buy-in for hydrogen.
2. Creating a new body to foster hydrogen production, transportation, storage and application technologies. This should operate across the devolved nations providing routes for communication between investors, regulators and stakeholders (such as the Environment Agency) in the name of scaling up the industry in a way that makes the most of the opportunities while properly managing risk, including safety and environmental risk. As with all new technological developments, the need for planning and regulation will need to be balanced with the need for pace and innovation. Sandbox strategies can be enacted by a regulatory body to enable rapid development of multiple solution pathways suitable for upscaling in order to both support technological development but also enhance investor confidence.

The focus on industrial clusters in the UK, and the growing knowledge and implementation around these, holds strong opportunities to anchor technological development and investment in the UK. This not only reduces the risk of UK organisations shifting production overseas but should positively impact job creation, local and national upskilling, and local and national economies.

There may be value in choreographing industrial clusters so that they are coordinated at the national-scale. This could see setting up areas focussed on hydrogen technologies supported by suitably modified planning rules. While it is commendable to pledge long-term commitment to hydrogen technology development and upscaling, this should not come with delays to implementing the deployment-ready technologies that we have today which may prove pivotal to catalysing the hydrogen sector in the near and intermediate term. Strategies to support the further demonstration and deployment of market-ready solutions need equal weight alongside those that focus on further technology development. These present the opportunity to reduce emissions now, contributing to climate mitigation strategies at pace, while stimulating demand and markets for low-carbon hydrogen while long-term technological developments are underway.

8.3. Regional perspective and business building

Fundamentally, more work is required to engage with a diverse range of stakeholders that need to buy-in to hydrogen policy in a structured manner across at least three important dimensions:

1. There is a need for the public and private sector to work together to identify local and regional opportunities, match opportunities of production and supply with demand and to secure investment.
2. There is a need to coordinate around developing and securing the skills needed for the immediate and long-term growth of the hydrogen economy.
3. There is a need for public consultation to understand and address both hopes and concerns around hydrogen.

An emerging theme is the need and appetite for strengthened industrial cluster-style regional collaboration, which partners academics, industry, and policymakers to cultivate ecosystems for hydrogen technology roll out. This not only has the potential to strengthen technology development and application, but also to stimulate regional mechanisms. Regional collaborations play a pivotal role in fostering industry growth, innovation, and investment, including in key enablers, such as skills programmes. This allows for the generation of entrepreneurial ecosystems and promotes community and stakeholder engagement both locally and regionally.

Stakeholder engagement throughout regional and local communities is imperative. Collaboration between universities and regional industry champions allows teaching and research to be shaped to meet the needs of local industry. This also leads to the strengthening and creation of internships, sponsored qualifications, and placements. Together, this adds significant value in building strong regional pools of skills, promoting upskilling and reskilling whilst simultaneously boosting jobs creation and stimulating local economies. The success of skills development both regionally and nationally is heavily dependent upon policy support from the UK Government. Sufficient funding paired with long-term support and commitment for a portfolio of educational strategies is paramount to successful development, scaling and implementation of net zero technologies more broadly, not just green hydrogen.

To address skills needs locally and nationally, new ways of learning and training must be developed locally and supported by individuals, employers, education, and training providers. To address this, government needs to:

- invest in a long-term STEM education and skills strategy that, among other things, provides a guarantee that all pupils receive high quality, up-to-date STEM careers advice and guidance;
- ensure funding is available to Universities, Colleges, and Schools for laboratory facilities to deliver the strategy;
- support and invest in stakeholders active within Local Skills Improvement Plans to develop new opportunities for micro-learning in support of upskilling and reskilling of local workforces in growth sectors supporting net zero; and
- support innovations in skills development such as ‘micro credentials’, new ‘bite-sized’ learning opportunities that can be studied flexibly and are designed to be accessible and inclusive.

Such initiatives go beyond hydrogen, and may deliver broader co-benefits; ensuring robust research, training and skills infrastructure will not only underpin the hydrogen economy but serve to support broader UK R&D and green skills needed for the pathway to net zero.

Policy intervention and support for inter-regional collaboration should prevent unnecessary competition and provide platforms for data and learning sharing as green hydrogen projects and initiatives are deployed. An overall temporally explicit spatial plan should be the end goal, with coordinated regional and local input. This can in turn feed into the further refinement and implementation of regional plans and policies. Here again, the responsibilities of the new NESO will be key. The role and responsibilities NESO has for Strategic Spatial Energy Planning and Centralised Strategic Network Planning can provide key components of the overall national vision and direction of travel. The role it will have in coordinating Regional Energy Strategic Planning could facilitate the identification of opportunities and challenges to be accounted for in national-level planning and addressed and delivered at the local and regional levels. This is provided that key local actors, such as local authorities are supported and resourced to contribute properly to these processes for their areas of coverage.

Encouraging co-ordination across government departments, especially those that have considerable overlap with wider industry needs, will be instrumental for successful co-creation of multidisciplinary industrial clusters. The challenge of developing a strong UK hydrogen economy is multifaceted and complex, and therefore will require government departments across policy areas to work in lockstep to identify and overcome barriers and seize opportunities for hydrogen development.

Refined industrial roadmaps could be used to influence creation of fit-for-purpose funding allocations on both a national and regional scale. Funding structures are often slow and can inadvertently lead to overlapping of funding for the same projects and work streams as well as poorly timed contracting times. Government-led policy support for regional development as described here would bolster infrastructure enhancement across the country.

Finally, as hydrogen production and demand need to scale up in tandem, there may also be a role for trading platforms that can match demand with supply, collating the resources available with potential customers in a particular locality. Industrial users, for example, are likely to be able to provide very clear information on their use rates and requirements. There is a lot of scope for innovation in this space.

8.4. Anchoring value in the UK

The context of hydrogen economy development at a global scale is both competitive and fundamentally unequal. Economic tools like Important Projects of Common European Interest (IPCEI) and the US Inflation Reduction Act (IRA) create an uneven playing field internationally. The UK could become a leader in hydrogen production and use, and may be able to position itself as an exporter of hydrogen technologies. The UK must create a vision for where it would like to position itself in the global hydrogen economy and ensure UK hydrogen development can compete to develop a favourable economic and policy environment.

The UK has fallen behind in converting scientific knowledge into commercial success[41]. Net zero technology development provides an opportunity to reverse this trend, particularly the transition to a hydrogen economy using relevant skills translated across from vulnerable sectors, such as oil and gas. Sustaining the economic benefits within the UK requires robust policies aimed at promoting domestic manufacturing, skills development, and innovation. However, it is also crucial to balance attracting international investment with supportive measures to retain investment and stimulate job creation. To support an ecosystem which allows businesses to thrive in the UK, policymakers could provide incentives for local manufacturing, to safeguard intellectual property rights, develop UK-based supply chains and create collaborative research initiatives. To secure international investment, contract conditions could be more ambitious in their requirements such as minimum levels of job creation.

To truly anchor value in the UK and ensure business growth contributes to the national economy, support from government would be most beneficial if delivered at key points in business development. These key stages are:

- the initial set up of the business;
- proof of concept and technology development, for example in the provision of space and facilities needed for testing and demonstration; and
- when accessing the required manufacturing base and investment needed to effectively scale up.

All these stages are enabled by the market confidence that can be bolstered by a long-term, well-evidenced strategy or roadmap, and also through showcasing technologies and following up their prototyping and providing long-term funding. A key lever available to government is public procurement. There may be scope to leverage procurement budgets and position key public sectors, estates, or facilities as large offtakers for green hydrogen to act as a spur to demand scale up.

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[41] Institute for Manufacturing, University of Cambridge. 2024. UK innovation report 2024. See https://www.ciip.group.cam.ac.uk/wp-content/uploads/2024/03/UK-Innovation-Report-2024_FINAL-20.03.24.pdf (accessed 5 July 2024).

8.5. Summary of key policy interventions and actions

There are three key areas that need to be addressed to ensure that the UK gains the maximum benefit and least disruption from a future hydrogen economy:

I **A roadmap for green hydrogen**

Developing and committing to a clear, detailed hydrogen roadmap for the UK will provide the direction necessary to achieve a successful hydrogen economy. The roadmap should include:

- An overarching vision as to where the UK would like to position itself in the global hydrogen economy. If a leading role is envisaged then robust policies will be needed, aimed at promoting domestic manufacturing, skills development, and innovation.
- A commitment to long-term consistency and ambition.
- Funding rounds for the development of green hydrogen technologies, which stretch over many years to support growth from R&D to full production.
- Adoption by all relevant government departments to work in unison to identify and overcome barriers and seize the opportunities arising from hydrogen development.

II **Support for commercialisation and scale up.**

It is important that the roadmap helps to provide long-term confidence and assurance for major capital investment in infrastructure and manufacturing facilities. In addition, refined industry specific roadmaps could be used to influence the creation of fit-for-purpose funding allocations at both a national and regional scale. Further support might include:

- The creation of a new body to foster hydrogen production, transportation, storage and application technologies. Trading platforms might be needed that can match demand with supply.
- The creation of hydrogen investment zones to foster industry conversion to hydrogen and the development of local, regional and national infrastructure.

III **Co-ordination for development and growth**

The development of a successful hydrogen economy will necessitate the co-ordination and balancing of hydrogen supply and demand across the country, and the associated design of a transport and storage system that is flexible enough to accommodate growth at the regional and local levels. This will require collaboration between national and local government, co-ordinated by NESO and aligned with the national hydrogen development goals and Local Area Energy Planning. There are many common areas of policy that will also need co-ordination, for example:

- Developing and securing the skills needed and ensure long-term support and commitment for a portfolio of educational strategies.
- Changes to existing regulatory and planning systems to achieve the scale of the green hydrogen capacity needed and at the pace required.

UK hydrogen roadmap timeline

TABLE 1

This timeline draws together the issues, opportunities and critical milestones arising within the report onto five-year timeframes.

	2025 to 2030
Infrastructure	Early demos and pilots for hydrogen uses, including E-fuels. Place-based innovation clusters are developed and will form the bedrock for future innovation. Regional production and distribution systems are developed, with production concentrated in industrial clusters, and join up nationally over time. Development of digital twins to guide system development, across heat and electricity, and over spatial scales. Increase in renewable energy production to ensure green hydrogen production. Scale-up of UK manufacturing for hydrogen technologies, Line packing potential explored further.
Finance and hydrogen economy development	Clear strategy for investment incentives and competitions. Clear, consistent, and long-term funding support will enable projects to move beyond demonstrator stage. Economic policies to support hydrogen innovation eg Faraday-like challenge. Continued and increased incentives to catalyse UK H_2 economy growth, mirroring those overseas (eg IRA). Clusters developed. Continue to promote small H_2 entrepreneurship .
Safety and environment	Increase in regional use in demonstrator and pilot projects will increase users. Develop comprehensive and regulated safety training for all end-users. Create regular testing regimes for emerging technologies. LCA guidelines further refined, based on better information and knowledge of leak detection and impacts of leaks and losses.

	2030 to 2035	2035 to 2040	2040 to 2045	2045 to 2050
	Expansion and installation of hydrogen infrastructure. Development of large-scale hydrogen storage solutions underway. Infrastructure development to be increased to keep pace with development of other technologies. Regional hydrogen production and distribution systems join up at a national scale. Continued demos and small-scale deployment of hydrogen for e-fuels and in industry (eg green chemicals). Exploration of solar and nuclear produced H_2. Establishment of first hydrogen gas networks, with potential for 100% hydrogen gas grid at local scales. Localised End-user adaptation for 100% hydrogen gas grid. Gas grid updated to facilitate H_2 line packing.	Continued advancement of storage, production, and distribution technologies. Salt cavern development well underway for energy storage. Wide scale end-use infrastructure begins to change to accommodate H_2 gas grid.	H_2 grid comparable to current electrical grid to meet net-zero targets.	
			Establishment of hydrogen trade at a sub-global level. Establishment of sub-global or global standards for hydrogen trade.	Hydrogen trade expands. Hydrogen end-uses previously identified and refined for optimal outcomes. Hydrogen widely used in identified optimal and cost-effective sectors.
	Continued advances in H_2 leak detection. Safety awareness training for end-users Advances in leak detection in large scale storage systems Increased need for open safety and environmental sharing across sectors as technologies and applications are deployed. R&D to decrease in reliance of rare materials to avoid supply chain issues. R&D to tackle water purity restrictions.	Risk – as hydrogen use increases and diversifies, contact with untrained personal increases. Widespread safety awareness needed to reduce risk to end-users. Gas system updated to include leak monitoring and safety. End-use infrastructure safety adaptations are necessary		Climate change poses a significant risk Safety measures put in place to mitigate risks from climate change.

TABLE 1 (continued)

	2025 to 2030
Skills	Further develop skills for hydrogen safety across industries. Establish industry-academia partnerships for training and skills development. Support for H_2 programmes in higher education systems and industry. Fund skills development programmes. A UK skills map, based on the expected skill needs across the H_2 economy, would help direct investment and funding towards skills.
R&D	Risk – Lack of availability of parts may be a limiting factor for tech deployment. R&D on electrolyser technologies, including efficiency improvements, circularity and recycling, and materials use. Identify sustainable supply chains of key raw materials for electrolysers and wider hydrogen system technologies. R&D on for geological H_2 storage in the UK. Continued and novel materials R&D to improve hydrogen technologies, including production, distribution, and use. Patent system reviewed to enable scale-up of emerging technologies. Research needed on fundamental science, including the role of water quality in electrolysis (and how to use lower quality water), how to improve membrane performance, how to reduce gas crossover and water bubbling, and how to maintain alkaline electrolyser performance at high currents. Research on operating fuel cells at high temperature for the aviation sector. Research on fuel performance at high altitudes. Research needed on non-climate impacts of hydrogen systems. Line packing explored further.
Regulation and public acceptance	A future energy system blueprint for hydrogen to clearly identify and communicate regulatory needs and investment opportunities. Regulatory frameworks developed for existing technologies and continually updated alongside development. Emerging regulation will impact the nascent H_2 sector, eg PFA bans. H_2 roadmaps and development must evolve to a changing wider regulatory landscape.

2030 to 2035	2035 to 2040	2040 to 2045	2045 to 2050
Expansion of skills and training for H_2 throughout the education system including STEM in schools and relevant courses at undergraduate and post-graduate levels and in industry. Retraining initiatives deployed to help transition of industry workforce into hydrogen. Risk of skills outflow if the UK's hydrogen economy is not adequately addressed. Skills gaps that have not been addressed become increasingly present and will persist.			
Supply chains for key materials established at scale. Supply chain risks broaden and evolve as H_2 technologies are increasingly deployed globally and competition for scarce resources grows. Continued R&D to overcome key obstacles such as gas crossover in electrolyser membranes. Improved technology designs to reduce NOx emissions. Sub-surface mapping data to guide infrastructure development. A hydrogen materials database established to help determine specifications for materials selection. AI increasingly integrated into energy systems. H_2 supply chain optimization to reduce reliance on precious metals and high-quality water.		Continued improvements in novel material development. Hydrogen used in aircraft at a small scale to demonstrate viability.	
Capability for testing and Q+A further developed alongside emerging uses of hydrogen. Regulation continually evolving. Lessons learned across regions and supply chains are shared.			

TABLE 1 (continued)

	2025 to 2030
Integration with UK systems	Whole system design used to identify future hydrogen system uses and make initial steps towards hydrogen system optimisation to guide development and funding. Centralised and decentralised approaches explored. Electrolysers positioned with a focus on longevity and spatiality of the future system. Whole-system optimisation would underpin industrial symbiosis. Climate adaptation built in to planning. Research will be needed on what a climate resilient H_2 system looks like.

2030 to 2035	2035 to 2040	2040 to 2045	2045 to 2050
Production targets for SAFs aligned with fuel-blend moderators.	Significant defossilisation of the UK energy system. Competition over access to clean water, exacerbated by climate change.	Observed and predicted climate impacts integrated into system improvements and resilience building. Shift towards climate adaptation strategies. Continued competition over resources including rare earth materials and clean water, unless recycling methods and electrolysers which can use low-quality water have been developed and deployed.	

Appendix

The Royal Society and Royal Academy of Engineering would like to acknowledge the contribution of the following individuals.

Steering group members
Chair: Nigel Brandon FRS FREng, Imperial College London
Fraser Armstrong FRS, University of Oxford
Sara Walker, University of Birmingham
Mark Selby FREng, Ceres Power

Workshop speakers and contributors
Alan Tolley, Independent consultant
Alex Reip, Oxford Nano Systems / Brunel University
Amer Gaffar, Manchester Metropolitan University
Angela Needle, Cadent Gas Limited
Caroline Hargrove, Ceres Power
Hervé Morvan, Rolls Royce
James Collins, ITM Power
Jane Toogood, UK Hydrogen Delivery Council
Jennifer Wen, University of Surrey
Joan Cordiner, University of Sheffield
John Irvine, University of St Andrews
Jon Hunt, Toyota
Kamran Iqbal, Electric Aviation Group
Katy Milne, Hydrogen Innovation Initiative
Liam Lidstone, Energy Systems Catapult
Mercedes Maroto-Valer, Herriott-Watt University
Meysam Qadrdan, Cardiff University
Mike Petch, Johnson Matthey
Neil Kermode, European Marine Energy Centre
Nilay Shah, Imperial College London
Paul Dodds, University College London
Paul Monks, Department for Energy Security and Net Zero
Peter Bruce, University of Oxford
Peter Williams, INEOS
Rachael Rothman, University of Sheffield
Rita Wadey, NESO Hydrogen
Robert Sorrell, Henry Royce Institute
Rupert Lewis, The Royal Society
Tim Mays, University of Bath
Xiaohong Li, University of Exeter

Observers
Sulekha Abdi, Department for Energy Security and Net Zero
Jeremy Brutus, Department for Energy Security and Net Zero
Simone Cooper-Searle, Department for Energy Security and Net Zero
Pete Newton, Department for Energy Security and Net Zero
Tom Mowle, Department for Energy Security and Net Zero
Anton Orpin-Massey, Department for Energy Security and Net Zero

Staff contributors
Andrew Chilvers, Royal Academy of Engineering
Paul Davies, Royal Society
Rupert Lewis, Royal Society
Leonardo Marioni, Royal Society
Luke Reynolds, Royal Society
Calum Savage, Royal Academy of Engineering
Liz Surkovic, Royal Society
Daisy Weston, Royal Society
Lynn de Miranda, Royal Society

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For further information
The Royal Society
6 – 9 Carlton House Terrace
London SW1Y 5AG

T +44 20 7451 2500
W royalsociety.org

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For further information
The Royal Academy of Engineering
Prince Philip House
3 Carlton House Terrace
London SW1Y 5DG

T +44 20 7766 0600
W raeng.org.uk

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