Hydrogen Innovation Initiative

The UK Hydrogen Innovation Opportunity

Hydrogen technology roadmaps

April 2024

The Hydrogen Innovation Initiative (HII)

HII is a trusted group of organisations bringing together key stakeholders to create an investible, globally competitive hydrogen technology and services sector, here in the UK. Our vision is for UK technology to power the global hydrogen economy – transforming UK industry into a net zero powerhouse.

HII partners:

Advanced Propulsion Centre UK, Aerospace Technology Institute, Catapult Compound Semiconductor Applications, Catapult Connected Places, Catapult Digital, Catapult Energy Systems, Catapult High Value Manufacturing, Catapult Offshore Renewable Energy, Catapult Satellite Applications, Glass Futures, NPL National Physical Laboratory, Net Zero Technology Centre

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Acknowledgments

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HII Industrial Advisory Board

The HII Industrial Advisory Board (IAB) is made up of experts bringing insight of the opportunities and challenges of the hydrogen economy from across the value chain, from production, distribution and consumption.

It brings expertise from the following organisations*:

Airbus, bp, Cummins, GKN Aerospace, H2GO Power, Hydrogen Energy Association, Hydrogen UK, Johnson Matthey, Macquarie, National Gas, ZeroAvia

*HII and the HII IAB do not represent the direct interests of the organisations.

This report provides an overview of cross-cutting hydrogen technology roadmaps. It has been produced as a supporting report to *The UK Hydrogen Innovation Opportunity*.

1

Overview

Hydrogen technology roadmaps

The global hydrogen technology market has potential to reach $1 trillion by 2050. Innovation in technologies that have application across multiple sectors will unlock the UK's access to this market.

The ***UK Hydrogen Innovation Opportunity*** lays out the vision for the UK to become a leading exporter of hydrogen technology, with a ten-year window of opportunity to convert investment in innovation into globally competitive supply chains. It sets out the size of the prize for the UK and highlights what is needed to make it happen.

The analysis in the ***UK Hydrogen Innovation Opportunity*** is underpinned by evidence and analysis contained in four supporting reports:

1. ***Hydrogen technology roadmaps* (this report)**
   A summary of the technology innovation opportunities for the UK in the hydrogen economy, based on stakeholder engagement and extensive literature review.
2. ***UK capabilities***
   An overview of the UK's current capability in hydrogen technologies and the critical enablers required for the UK to maximise its potential in the hydrogen technology market.
3. ***Sectors and scenarios***
   A summary of sector needs for hydrogen and hydrogen technologies, globally and in the UK, up to 2050 and modelled UK scenarios.
4. ***Techno-economic methodology***
   A method statement explaining the analysis behind the hydrogen economy and technology market figures quoted in the reports ***UK Hydrogen Innovation Opportunity*** and ***Hydrogen technology roadmaps***.

This report lays out roadmaps for the nine technology families identified in the ***UK Hydrogen Innovation Opportunity***. The content in these roadmaps has been developed through a combination of extensive industrial engagement and aggregation of existing sector and technology roadmaps. This document also signposts to reports that highlight innovation challenges and opportunities for two underpinning technology families - materials and digital.

The technology roadmaps in this document each include the following:

- UK and global market forecast for 2030 and 2050 for the respective technology family.
- Key technologies that make up the technology family.
- The associated innovation opportunities associated with each key technology together with development and industrialisation timelines and the sectors that will benefit from the innovation.

The list of innovation opportunities on each roadmap is by no means exhaustive, but they are a sample that were selected because they highlighted some key innovation actions for the UK. To make this selection, a range of factors were considered including global and UK economic demand, the UK political imperative and UK potential to win market share. The development and industrialisation timelines are recommendations only and do not signify that this work is already planned or funded.

Figure 1. Hydrogen technology families and underpinning technology families

Hydrogen technology families

Production technologies

Technologies associated with the methods to produce low carbon hydrogen, as defined by UK low carbon hydrogen standard.

- Biomass handling and reforming
- Carbon capture enabled hydrogen production
- Electrolysers
- Non-electrolytic production

Hydrogen as a feedstock and carriers

Technologies associated with hydrogen used as a feedstock in production processes including chemical processing and material production.

- Hydrogen carrier technologies
- Synthetic Aviation Fuels (SAF) and e-fuels synthesis

Propulsion and power generation

Technologies associated with the use of hydrogen for propulsion or to generate power.

- Fuel cells
- Gas turbines
- Internal combustion engines

Heat generation

Technologies associated with the use of hydrogen for heat, considering industrial and commercial applications.

- Emissions control
- Hydrogen gas and flame monitoring
- Refractories

Storage

Storage technologies for hydrogen as a gas, liquid or using carriers, at numerous scales and for numerous applications.

- Compressed storage tanks
- Cryogenic storage
- Large-scale storage
- Solid-state storage

Distribution and control

Technologies required to safely distribute and deliver hydrogen, covering both infrastructure and on-vehicle solutions.

- Control valves
- Cryogenic pumps
- Hydrogen-capable pipes
- Refuelling systems

Conditioning

Technologies to prepare hydrogen for distribution and use.

- Compressors
- Liquefiers
- Purification and separation

Electrical and thermal management

Technologies associated with electrical and thermal management for end-to-end hydrogen use.

- Power electronics
- Thermal management

Metering and monitoring

Application of sensors and monitoring systems to ensure the safe and efficient operation of hydrogen systems.

- Distribution pipeline inspection
- Flow meters
- Hydrogen purity analysis
- Leak detection

Underpinning technology families

Materials

New materials and material recycling methods enabling higher performing and more sustainable products across the hydrogen economy.

Digital

Digital technologies to enable system, product and process design; for asset monitoring and for robust certification of hydrogen.

Sectors in a hydrogen economy

Production

Production
- Electrolytic
- Non-electrolytic

Storage & Distribution

Storage
- Large-scale storage
- Small-scale storage

Distribution
- Pipeline distribution
- Mobile distribution
- Refuelling infrastructure

Use

Industry
- Industrial heat
- Chemical

Power generation
- Grid support
- Site specific
- Backup/auxiliary

Transport
- Aviation
- Maritime
- Rail
- Road and off-highway

Domestic and commercial heating*
- Domestic and commercial heating

* Hydrogen for domestic and commercial network heating, if adopted, significantly impacts distribution and consumption.

The underlying technology required to facilitate hydrogen adoption for this market has been considered in the technology roadmaps, however domestic and commercial boilers have not been considered.

Details on hydrogen heating's impact on the hydrogen market can be found within the ***UK Hydrogen Innovation Opportunity Sectors and scenarios report***.

The icons shown here are used throughout this report to indicate relevance of innovations to sectors.

2

Roadmaps

Production technologies

Summary: Electrolytic and non-electrolytic technologies are common ways to produce hydrogen, vital in both large-scale and localised production. Electrolytic production creates hydrogen from water and electricity, with oxygen as a by-product, whilst other methods use different feedstocks or thermal processes. Biomass may play a key role with its ability to be carbon negative, whilst electrolysis may provide a route for long-term grid balancing.

Global and UK market forecasts

These tables show forecasts for the annual global and UK market for this technology family. The figures show the neutral (midpoint) scenario from analysis for HII by Markets and Markets [1].

2030		2050	
UK	Global	UK	Global
$3.45bn	$59bn	$2.31bn	$249bn

Now | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2035 | 2040 | 2045 | 2050

Biomass handling and reforming

Current state: Biomass hydrogen production methods using consistent feedstocks are mature. Processes using variable feedstock with high carbon capture rates are still immature.

- Increased process flexibility by utilising a broader range of feedstocks without pre-treatment enabling **cost** reductions
- **Efficiency** of carbon capture from hydrogen in syngas

Carbon capture enabled hydrogen production

Current state: Carbon capture technology within low carbon hydrogen production routes is mature, but currently unable to achieve 100% capture rates. Global projects are underway to demonstrate this technology at scale.

- Improve **efficiency** of carbon capture rates for low carbon hydrogen

Electrolysers

Current state: Proton exchange membrane (PEM) and alkaline electrolyser technology are mature and available, with development needed to improve key performance criteria. Alternative electrolyser technology to meet these needs are being developed.

- Monitoring and automation to enable **scalable and repeatable manufacture** of mature and reliable UK electrolyser technology
- Improve **efficiency** of electrolysers operating with intermittent and variable power supplies
- **Durable** components such as membranes for proton and anionic or ceramics for solid oxide
- Develop high-pressure electrolysis to increase **efficiency** and reduce **operational costs**
- **Resource-efficient** use of and development of routes to **recycle** and **re-utilise** critical materials (such as critical raw materials and platinum group metals)
- Improve **efficiency** through current density and reduced start-up time
- Improve **efficiency** through high power density electrolysers

Non-electrolytic production

Current state: Non-electrolytic hydrogen production methods, such as biogas/natural gas pyrolysis, thermochemical water splitting and chemical looping reforming have different maturity levels. Some of these methods require development to demonstrate competitive cost and efficiency.

- Research and develop **competitive** non-electrolytic production methods such as chemical looping reforming, pyrolysis and plasma splitting
- Materials for **durable** process apparatus able to withstand harsh environment (high-temperature, corrosion)

KEY: Technology Development — Technology Industrialisation

Hydrogen as a feedstock and carrier

Summary: To satisfy global needs and enable distribution of low carbon energy resources, transport of energy over long distances is required. Hydrogen chemical carriers, such as ammonia, have been identified as likely candidates to achieve this. Efficient conversion of energy into a transportable carrier, and conversion into a useable form at the point of need is critical in making this economically and environmentally viable. Numerous studies have investigated if centralised or decentralised production and conversion are the most viable, with a mixture the most probable. The co-location of sites producing and using feedstock is vital for the competitive production of hydrogen containing platform chemicals. Hydrogen is an essential feedstock in the production of Synthetic Aviation Fuels (SAF) and e-fuels that have potentially huge export opportunity and domestic applications to achieve decarbonisation. These green fuel sources must become cost competitive and readily available if they are to be as viable as conventional fuels.

Global and UK market forecasts

These tables show forecasts for the annual global and UK market for this technology family. The figures show the neutral (midpoint) scenario from analysis for HII by Markets and Markets [1].

2030	
UK	Global
$0.28bn	$9bn

2050	
UK	Global
$2.28bn	$288bn

Now | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2035 | 2040 | 2045 | 2050

Hydrogen carrier technologies

Current state: Hydrogen carrier technologies, including ammonia are mature and available. Ammonia is one of the most mature carriers with an existing global infrastructure for its production and transportation (primarily as a feedstock for fertiliser) and is only used as an example here. Further developments are required to meet future market requirements.

- **Efficient** hydrogen carrier production methods, such as high-yield, low-energy production of ammonia
- **Durable**, energy **efficient** recovery of hydrogen from carriers, both centralised and decentralised, such as decentralised low-temperature ammonia crackers with long life catalysts
- Develop **reliable** technology for direct use of hydrogen carriers to reduce **cost**, such as catalysts suitable for ammonia

Synthetic Aviation Fuels (SAF) and e-fuels synthesis

Current state: The maturity of SAF synthesis methods varies. Hydrotreated Esters and Fatty Acids (HEFA) are the most mature with synthesis of fuels such as 'power to liquid' and 'power to gas' requiring development. Further work is needed on conversion efficiency and cost to increase competitiveness.

- Assessing existing infrastructure to maximise **cost** effective usage in the production, distribution and deployment of SAF / e-fuels
- Increasing **efficiency** of SAF / e-fuel production, such as optimisation and contaminant resistance of catalysts
- Develop **robust**, **sustainable**, **competitive** bio-based and chemocatalytic pathways, technologies and processes to produce platform chemicals

KEY: Technology Development

Technology Industrialisation

Propulsion and power generation

Summary: Three propulsion technologies will see natural deployment into key sectors. Fuel cells and internal combustion engines are typically suited to medium to high-duty demands with long-range requirements and where refuelling can be centralised at key hubs, such as Heavy Good Vehicles (HGVs), and coaches. This is reliant on the availability of refuelling infrastructure and the technology becoming cost competitive with battery electric vehicles. Fuel cells could also see migration into more demanding applications, such as short-range flight, but require a step change in technology to improve performance and reliability. Direct combustion of hydrogen is seen as a natural transition for internal combustion engines, with the key advantage being minimal change to the existing technology and supply chains. Direct combustion of hydrogen through turbines is seen as a possible method to decarbonise higher power applications, such as power generation or short-medium haul flights. Hydrogen combustion processes need to be managed to minimise other emissions such as NO_X.

Global and UK market forecasts

These tables show forecasts for the annual global and UK market for this technology family. The figures show the neutral (midpoint) scenario from analysis for HII by Markets and Markets [1].

2030	
UK	Global
$0.12bn	$8bn

2050	
UK	Global
$5.25bn	£150bn

Now | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2035 | 2040 | 2045 | 2050

Fuel cells

Current state: Many fuel cell technologies are mature and readily available. Development is needed to improve durability and efficiency such as through novel high-temperature Proton Exchange Membrane (PEM) fuel cells.

- Monitoring and automation to enable **scalable and repeatable manufacture** including the stack
- Improved integration of balance of system equipment to increase **efficiency** and reduce **cost**
- High temperature/**efficient** fuel cells reducing mass and increasing operating life
- **Durable** long life fuel cells and membranes, able to withstand impurities and harsh environments
- **Resource-efficient** use of and development of routes to **recycle** and **re-utilise** critical materials (such as critical raw materials and platinum group metals)

Gas turbines

Current state: Hydrogen gas turbine technology maturity varies depending on the blend of hydrogen. Low hydrogen concentrations using existing gas turbine designs are the most mature with existing designs thought to be suitable. Further development is required for higher hydrogen concentrations.

- Incremental solutions using modification to existing designs to improve **durability** @ <100% hydrogen
- Material and monitoring solutions for combustion to improve **durability** @ 100% hydrogen
- Control and operational parameters to mitigate NO_x **emissions** without impacting **efficient** performance @ 100% hydrogen

Internal combustion engines

Current state: Hydrogen internal combustion engines are being matured, with several leading manufacturers bringing products to market; other manufacturers are also developing solutions. Activity is required to improve performance and increase competitiveness.

- Improve **performance** of retrofittable hydrogen and dual fuel engines
- Improve **efficiency** through optimising hydrogen combustion and waste heat recovery
- Reduction of NO_x **emissions** through development of improved abatement systems

KEY: Technology Development — Technology Industrialisation

Heat generation

Summary: Hydrogen will play a role in decarbonisation of high energy demand sectors where there are limited other alternatives met with fossil fuels. The burning of hydrogen as a heat source within these high energy demand sectors, such as foundation and food and drink industries, will require adaptation of current fossil fuel technologies.

To facilitate this transition, existing processes must be able to safely use hydrogen without effecting equipment life, whilst operating efficiently. Emissions abatement solutions able to manage by-products of hydrogen combustion, such as NO_x and carbon, must be developed.

Global and UK market forecasts

These tables show forecasts for the annual global and UK market for this technology family. The figures show the neutral (midpoint) scenario from analysis for HII by Markets and Markets [1].

2030		2050	
UK	Global	UK	Global
$0.09bn	$2bn	$0.49bn	$14bn

Now	2025	2026	2027	2028	2029	2030	2035	2040	2045	2050

Emissions control

Current state: Hydrogen for process heating has been demonstrated across several foundation industries. Challenges regarding the control, detection and response to NO_x emissions still require further research, particularly in applications where operating parameters are likely to produce emissions.

Simulation and monitoring of hydrogen flame to optimise **efficient** combustion conditions

Understand performance of existing abatement systems for development of low-**cost** adaptation and redevelopment to suit hydrogen combustion

Low-**cost** dedicated **efficient** abatement systems for hydrogen combustion

Refractories

Current state: Use of hydrogen within process heating is mature and has been demonstrated. Research is required to better understand, optimise and develop suitable refractory materials to resist deterioration under the different conditions experienced when using hydrogen in place of natural gas.

Develop methods, standards and **test** capabilities to replicate, understand and **certify** through-life performance

Efficient and **durable** refractory materials for hydrogen furnace conditions

Hydrogen gas and flame monitoring

Current state: Gas and flame monitoring technology for industrial process heat applications using conventional fossil fuels is mature. Due to hydrogen flames being within different spectra, development is required to adapt or develop new solutions that are hydrogen suitable.

Develop sensors and methods to predict hydrogen flame conditions for **efficient** and **safe** operation

KEY: Technology Development — Technology Industrialisation

Storage

Summary: Storage is critical at every scale for the future of hydrogen adoption, from on vehicle storage to large-scale long-duration grid balancing. Storage is a significant challenge due to the low volumetric density of hydrogen, requiring either high pressures, cryogenic temperatures or use of emerging and novel storage mediums. Storage solutions must be able to meet these harsh requirements, whilst remaining safe and produced at a cost that enables scale-up. The different storage technologies each provide different advantages and limitations and are therefore selected against specific requirements.

Global and UK market forecasts

These tables show forecasts for the annual global and UK market for this technology family. The figures show the neutral (midpoint) scenario from analysis for HII by Markets and Markets [1].

2030		2050	
UK	Global	UK	Global
$0.26bn	$8bn	$3.53bn	$62bn

Now | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2035 | 2040 | 2045 | 2050

Compressed storage tanks

Current state: Metallic and non-metallic compressed storage tanks are a mature technology, with composite storage tanks the norm for mobility applications. Innovation is required to meet cost, mass and end-of-life requirements.

- **Scale up** of manufacturing of certified non-metallic hydrogen storage using full automation
- **Develop** high gravimetric efficiency tanks with maximised service life
- **Material recovery** and reuse of non-metallic tanks

Cryogenic storage

Current state: Cryogenic storage technologies are mature and readily available, but often have limitations. Suitable materials to meet the increasingly stringent requirements of mass and long life with minimal loss of hydrogen are under investigation and are still immature.

- Testing capabilities for fundamental understanding of material properties and **durability**
- In-service monitoring of cryogenic fuel tanks to ensure **safe** operation
- **Energy-efficient** boil-off management to reduce energy use and hydrogen **emissions**

Large-scale storage

Current state: Salt caverns are the most mature large-scale storage solution. Depleted field storage has been demonstrated and has potential for energy resilience; however, the assessment of cost and losses means that further consideration is required. Lined underground storage is an emerging alternative offering possible storage for lower quantities suitable for industrial applications.

- **Upscaling**, deployment and filling of salt cavern storage of hydrogen
- Assessment of depleted fields cost and hydrogen **losses** due to factors such as leakage and bacterial consumption
- Development of **cost** efficient lined underground storage using suitable **durable** materials

Solid-state storage

Current state: Some technologies are nearing maturity, with alternative technologies still under development. The focus of this technology is reducing cost and storage pressure compared to compressed storage, mostly for non-mass sensitive applications.

- Low-cost materials and **high-efficiency** systems for localised storage
- Materials and system for improved hydrogen absorption/release **performance**
- **Resource efficient** use of and development of routes to **recycling** and **re-utilisation** of critical materials (such as critical raw materials and platinum group metals)

KEY: Technology Development — Technology Industrialisation

Distribution and control

Summary: Hydrogen must be distributed safely from production to point of use at industrial sites and on vehicles. National distribution and transmission networks will comprise of repurposed and new valves, pumps and pipelines. Minimising hydrogen leakage and predicting residual life of distribution systems is critical for safe deployment.

The transport sector needs reliable, safe and fast methods for refuelling and on-vehicle distribution of hydrogen. Refuelling times and hydrogen loss need to be minimised, without compromising integrity of on-vehicle storage or distribution systems. On-vehicle distribution and pumps need to meet stringent mass, cost and safety requirements.

Global and UK market forecasts

These tables show forecasts for the annual global and UK market for this technology family. The figures show the neutral (midpoint) scenario from analysis for HII by Markets and Markets [1].

2030		2050	
UK	Global	UK	Global
$0.32bn	$8bn	$1.38bn	$29bn

Now | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2035 | 2040 | 2045 | 2050

Control valves

Current state: Hydrogen control valves for some applications are mature and available. For new and emerging applications maturity, cost, or supply chain capacity are limiting.

- **Asset integrity** of existing gas network through inspection and monitoring for repurpose and life extension of assets
- Design solutions for **safe** and **reliable** leak-free gas valves
- **Safe** leak-free, durable, thermally-isolated and **efficient** cryogenic valve

Cryogenic pumps

Current state: Many cryogenic liquid hydrogen pumps are mature and available. Development is needed on pumps for new and emerging applications with challenging operating conditions, such as on-vehicle.

- Low **mass** and **efficient** on-vehicle cryogenic pumps
- Improvement of **durability**, life in service, **efficiency** through development of low loss and energy consumption cryogenic pumps

Hydrogen capable pipes

Current state: Suitable materials for hydrogen-capable pipes are understood. Alternative materials to address specific challenges for new infrastructure are being developed. Methods to ensure through-life integrity are required for all solutions.

- **Asset integrity** of existing gas network assets for repurpose and life extension
- Development of **durable** and **safety** accredited cryogenic pipe, such as for on-vehicle applications
- Low-**cost** material and design solutions for new, easy to deploy pipeline

Refuelling systems

Current state: Automotive hydrogen refuelling stations are mature and deployed globally. Iterative improvement is needed to improve efficiency and safety. Refuelling for other applications, such as aerospace and maritime is less mature and requires development.

- **Safety** protocols for optimised lower **cost** and **faster** refuelling rates
- **Cost-effective**, certified mobile refuelling solutions for fleets and off-highway vehicles
- Develop **safe**, low-**cost** cryogenic connectors

KEY: Technology Development — Technology Industrialisation

Conditioning

Summary: Conditioning of hydrogen is needed across the entire hydrogen value chain and may involve change in pressure, purity or state. The low volumetric density of hydrogen requires either high pressures or liquefaction for space constrained applications, often reliant on significant energy and technologies with scalability or technical limitations. Early distribution and deployment of hydrogen has been dependent on pressurisation, with this technology remaining an integral part of new infrastructure and end uses. Emerging sectors, such as aerospace, are investigating liquid hydrogen due to the higher volumetric and mass efficiencies of the fuel and storage solutions respectively. Hydrogen purity can be critical for some applications, such as some fuel cell technologies; contamination risks throughout production and distribution must be addressed through purification.

Global and UK market forecasts

These tables show forecasts for the annual global and UK market for this technology family. The figures show the neutral (midpoint) scenario from analysis for HII by Markets and Markets [1].

2030	
UK	Global
$0.13bn	$5bn

2050	
UK	Global
$1.17bn	$32bn

Now | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2035 | 2040 | 2045 | 2050

Compressors

Current state: Compressor technology maturity varies, with material and seal development needed to improve reliability and performance. Emerging compressor technologies, such as electrochemical are still undergoing development.

- High-pressure compressors with improved **reliability** and service intervals
- **Smaller**, high **efficiency** compressor for high-volume low-pressure applications
- Competitive hydrogen electrochemical compressors through improved membrane **durability**

Liquefiers

Current state: Small-scale hydrogen liquefaction processes are an established technology. Development is needed to increase the scale and reduce energy consumption.

- Diversification and **upscaling** of existing liquefier producers to meet short-term needs
- Increase **efficiency** through reduced energy usage throughout the liquification process at all scales of production

Purification and separation

Current state: Hydrogen purification technologies for industrial scale applications, such as through pressure swing adsorption are mature. Some existing technologies require development to advance efficiency with novel and smaller scale technologies requiring development to increase longevity.

- Improve **efficiency** and reduce **cost** through developing materials with increased impurity capture rates for pressure swing adsorption processes
- Low-**cost**, **reliable**, impurity tolerant separation membranes to produce high purity hydrogen

KEY: Technology Development — Technology Industrialisation

Electrical and thermal management

Summary: Many sectors and net zero enabling technologies, including hydrogen enabled electrification, are reliant on power electronics. This will drive a significant increase in demand over the coming years. Another prevalent subsystem is thermal management, which is vital to the efficiency and longevity of numerous hydrogen technologies. Improving efficiency and tailoring of these subsystems to the requirements of hydrogen applications is key to the successful roll out of hydrogen and may play a key role in cost and performance differentiation.

Global and UK market forecasts

These tables show forecasts for the annual global and UK market for this technology family. The figures show the neutral (midpoint) scenario from analysis for HII by Markets and Markets [1].

2030		2050	
UK	Global	UK	Global
$0.01bn	$0.2bn	$0.32bn	$13bn

Now | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2035 | 2040 | 2045 | 2050

Power electronics

Current state: Power electronics are mature and already adopted across many sectors and applications. Optimising the trade-off between performance and cost for hydrogen specific applications is needed.

- Increase **efficiency** through development and scale up to MW and GW of DC/DC power converter
- Increase **efficiency** through development of fast dynamic systems with improved filtering, including adoption of higher switching frequencies
- **Cost** reduction through standardisation and modularisation of power conversion to enable off the shelf solutions for fuel cells and electrolysers

Thermal management

Current state: Thermal management systems are mature and adopted across many sectors and applications. More cost effective and power dense solutions for new and emerging hydrogen applications is required.

- Improve **efficiency** of thermal management systems for low-temperature fuel cells, including low drag radiators
- Development of **efficient** thermal management systems for high-temperature fuel cells
- Development of **efficient** and **smaller** systems for gasification of liquid hydrogen, providing cooling for propulsion systems

KEY: Technology Development — Technology Industrialisation

Metering and monitoring

Summary: There is a need for sensors and monitoring systems across all sectors to build public and industrial confidence. Safety drives the need for hydrogen detection, with hydrogen providing a risk at a larger range of mix ratios with air than natural gas. Furthermore, measurement of hydrogen emission is needed to prevent environmental impact. Methods to measure quantity, composition and purity of hydrogen in real time are required to enable reliable distribution and trading [2], [3].

Global and UK market forecasts

These tables show forecasts for the annual global and UK market for this technology family. The figures show the neutral (midpoint) scenario from analysis for HII by Markets and Markets [1].

2030		2050	
UK	Global	UK	Global
$0.02bn	$0.9bn	$0.38bn	$6bn

Now | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2035 | 2040 | 2045 | 2050

Distribution pipeline inspection

Current state: Inline inspection of pipelines when using natural gas is well established. Hydrogen presents new challenges, such as embrittlement, that requires new methods to ensure asset integrity for both new and repurposed pipelines.

- Pipeline inspection technology to meet **asset integrity** standards and detect embrittlement

Flow meters

Current state: Flow meters for hydrogen use a range of different methods that are at different stages of maturity. Challenges of increased flow rates and potential for leakage drive a need to develop reliable and low-cost hydrogen flow meters.

- Development of **accurate** flow measurement methods

Hydrogen purity analysis

Current state: In-service hydrogen purity and composition analysis technology is immature with many applications relying on lab-based activity for detailed analysis. Distributed real time purity analysis is required.

- Development of high frequency low-**cost** hydrogen purity sensors
- Development of high frequency low-**cost** hydrogen composition sensors

Leak detection

Current state: Leak detection technology is mature for many applications. Hydrogen use in emerging applications, including for indoor environments and populated areas, requires development of best practice and detection technology.

- Hydrogen monitoring regulations for **emissions** and **safety** across applications
- Sensor technology able to reliably measure low Hydrogen concentration (<1%). For prolonged **emissions** and **safe** mass market adoption

KEY: Technology Development — Technology Industrialisation

3

Underpinning technologies

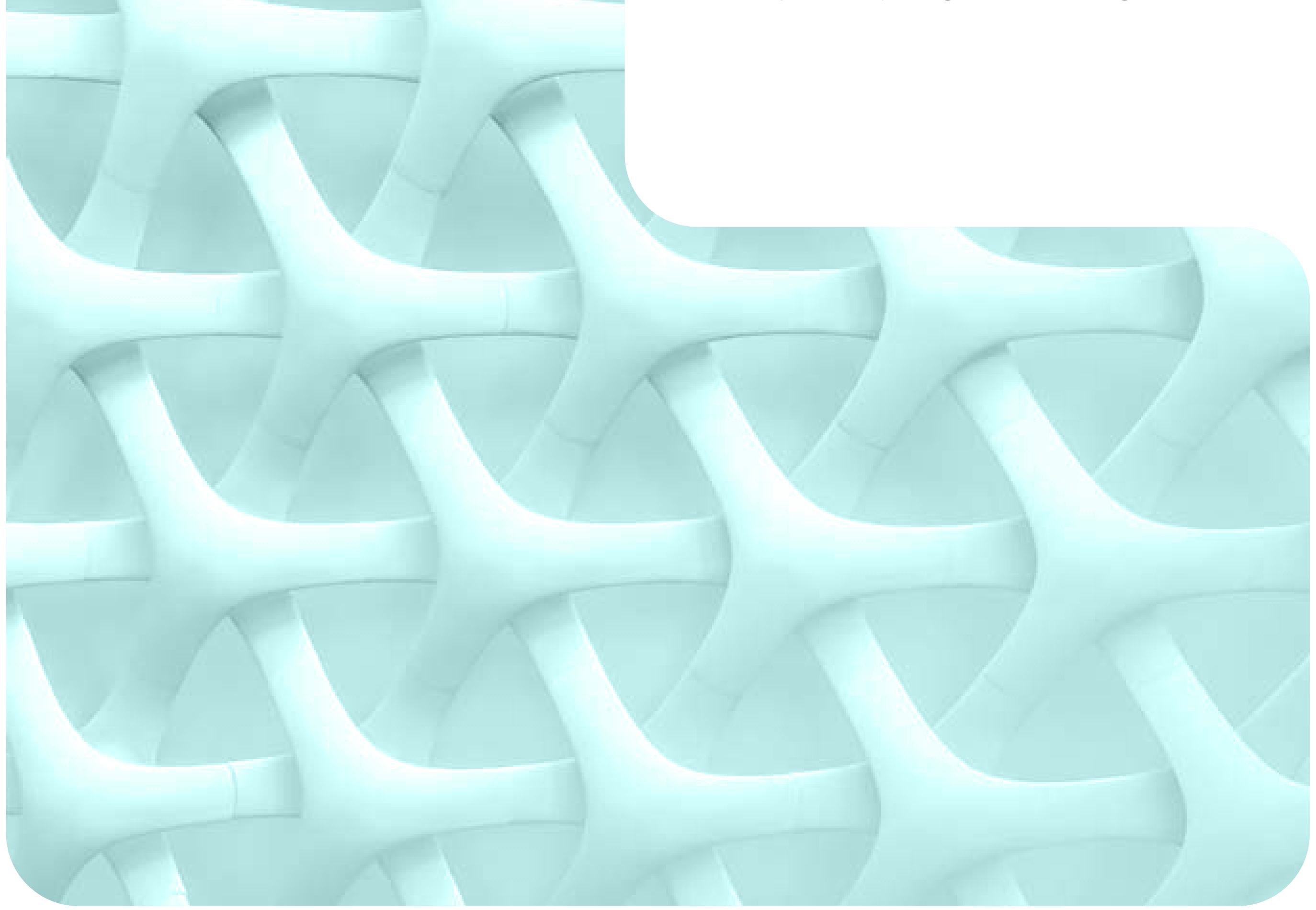
Materials

Digital

Materials

Materials validated for use with hydrogen will be critical to realise a new hydrogen economy

A report written by the Henry Royce Institute titled *Materials for End-to-End Hydrogen* [4] offers a comprehensive summary of the materials technology areas that have the potential to contribute to realising hydrogen deployment at scale. Further work involving an extensive network of industry and academic researcher produced a series of blueprints identifying the key materials challenges facing the UK starting with electrolysis and test. These are reflected where appropriate as innovation opportunities in these roadmaps for hydrogen technologies.



> **The UK needs further co-ordinated cross sector initiatives to overcome material challenges in order to accelerate development times of hydrogen technology.**

The priorities identified in the *Materials for End-to-End Hydrogen* report were further distilled into a set of five key areas which have formed the basis for the Royce Hydrogen Accelerator:

- **Production**
  Materials-led solutions to radically improve performance, reduce cost, and extend operational lifetimes of green electrolysis routes.
- **Storage**
  Robust structural materials to enable large-scale hydrogen storage for fixed and mobile applications.
- **Distribution**
  Materials capable of sustaining the thermal and mechanical strains associated with transporting hydrogen and purifying at point of use.
- **End-use**
  Materials to withstand the full temperature range required for hydrogen use – from cryogenic liquid hydrogen to transport and fuel switching applications that operate at over 1000° C.
- **Operational monitoring**
  Smart materials for real-time monitoring of critical infrastructure with the ability to report, mitigate or resolve problems before or as they arise.

The Royce report also identified key, cross-cutting research and technology enablers, that will increase the impact and accelerate materials research and have particular importance to support materials for hydrogen use:

- **Creating consistent lifecycle analysis approaches and data sets –** developing consistent definitions and approaches alongside transparent and accessible databases to support lifecycle analysis of materials.
- **Improving end-of-life treatment of materials –** designing products for end of life to enable materials recovery and reuse, and minimise waste creation.
- **Developing UK capability to test, set standards, and accredit new materials –** developing standardised testing methodologies to allow comparison of experimental results, and understanding materials degradation mechanisms, to develop testing and inspection protocols.
- **Computational design of materials -** using artificial intelligence to lead the design of materials with specified properties and accelerate the discovery of candidates.

Digital

The hydrogen economy has a unique opportunity to be data-driven from day one

A white paper written by Digital Catapult titled *Digital Solutions for the Energy Sector* [5] provides a summary of the growth in investment in energy specific digital technologies and the role they are playing in empowering the sector in its green digital transition. These are reflected where appropriate as innovation opportunities in these roadmaps for hydrogen technologies.

> **The hydrogen economy has a unique opportunity to be data driven from day one.**

The opportunities identified in the *Digital Solutions for the Energy Sector* white paper have been broadley broken into two specific areas. The paper identifies several challenges and opportunities that are shared by many different energy vectors, electricity, natural gas, hydrogen, and a whole host of different renewables. These are:

- **AI for flexibility**
  To make the most of these resources and ensure balance requires shifting demand to match generation, and storing energy for future use. Advanced analytics play a key role in determining when to utilise hydrogen and when to make best use of energy vector.
- **Digitalising New Energy Infrastructure**
  Developing net zero infrastructure, across generation, distribution, storage and end use provides opportunities to utilise digital tools to manage the build and operation of new facilities, making delivery at the required scale and pace feasible.
- **Data Interoperability Across the Sector**
  Ensuring that data is interoperable across the hydrogen economy as well as the wider energy sector to enable greater collaboration and data exploitation across the sector.

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In addition to challenges shared by multiple different energy types, there are also challenges and opportunities that are unique to a new hydrogen economy:

- **New Supply Chains**
  The growth in the hydrogen economy offers huge opportunities for greenfield supply chains, allowing existing players and new emergents to make use of a wide range of digital tools, without the need to retrofit with legacy systems.
- **Transparency and Certification**
  Tracking the provenance and purity of hydrogen from generation through to end use with digital ledgers provides confidence in purchasing low carbon hydrogen as well as guaranteeing that the fuel comes from a verifiable source.
- **Digital Skills for a Hydrogen Workforce**
  Utilising digital skills with energy domain expertise opens up a wide range of opportunities in design, operation and management of the energy system.

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