Hydrogen Innovation Initiative

The UK Hydrogen Innovation Opportunity

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:

Supported by Innovate UK

Acknowledgments

The ***UK Hydrogen Innovation Opportunity*** and supporting reports have been created with the invaluable contributions of leaders and experts who generously shared their time and insights. Their willingness to participate in interviews, provide data, and offer their perspectives, has significantly enriched the content and strengthened the reports' relevance to industry. We are truly grateful for their support.

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.

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Preface

The UK Hydrogen Innovation Opportunity for the first time, brings together the varied insights from published data, combined with market analysis, direct input from leaders and key stakeholders across the hydrogen landscape to create a consensus view in one report. The purpose of the report is to cut through some of the complexity that exists by building a common understanding of the opportunity that the emergent global hydrogen economy presents the UK and to what extent innovation must play if the UK is to become truly world leading.

The report considers the full end-to-end nature of the hydrogen economy to ensure there is a common understanding of the economic opportunity it could represent by 2050. Insights from across industry have brought clarity to both market and technology requirements, identifying four focus areas that represent the greatest potential benefit for the UK. It highlights the steps needed to build the UK industrial capability and capacity to position the UK as a market leader.

The UK Hydrogen Innovation Opportunity has been developed with, and for, industry with the first phase of industrial engagement involving over 250 businesses and 12 sector bodies. A second phase of industrial engagement will expand to a broader set of consulted stakeholder groups, concluding with a report entitled Hydrogen Innovation: The Case for Action in summer 2024. This will seek to validate the proposed focus areas, provide more detailed scope definition, the size of the opportunity and outline the steps required to secure them for the UK.

Executive summary

This report sets the context for the global hydrogen economy to reach $8tn annually by 2050, driven by the critical role hydrogen will play in delivering net zero. Although the technology required to make this a reality is known, it is not yet available at the scale or the economics that support adoption. Yet, the demand for hydrogen technology is expected to increase to $1tn annually by 2050. Innovation binds the two, providing a route for nations to stake a claim on their share of the hydrogen technology market and to influence the evolution of the global hydrogen economy.

For the UK, securing a 10% share of the technology market will be key and this will carry with it a three-fold benefit:

1. **Economic:** Increasing UK economic benefits and job creation by addressing a high growth, global export market.
2. **Decarbonisation:** Establishing resilience in the UK's net zero pathway including delivering the 10GW low carbon hydrogen production ambition by 2030.
3. **Influence:** Securing a leadership position for the UK and influencing where the value will be anchored.

This share of the technology market alone could deliver £46bn per annum to the UK economy by 2050, including 410,000 jobs across the end-to-end of the hydrogen economy. Achieving a leading position in the hydrogen technology market would create a platform for the UK to secure benefits from the wider hydrogen economy and could increase the broader impact ten-fold.

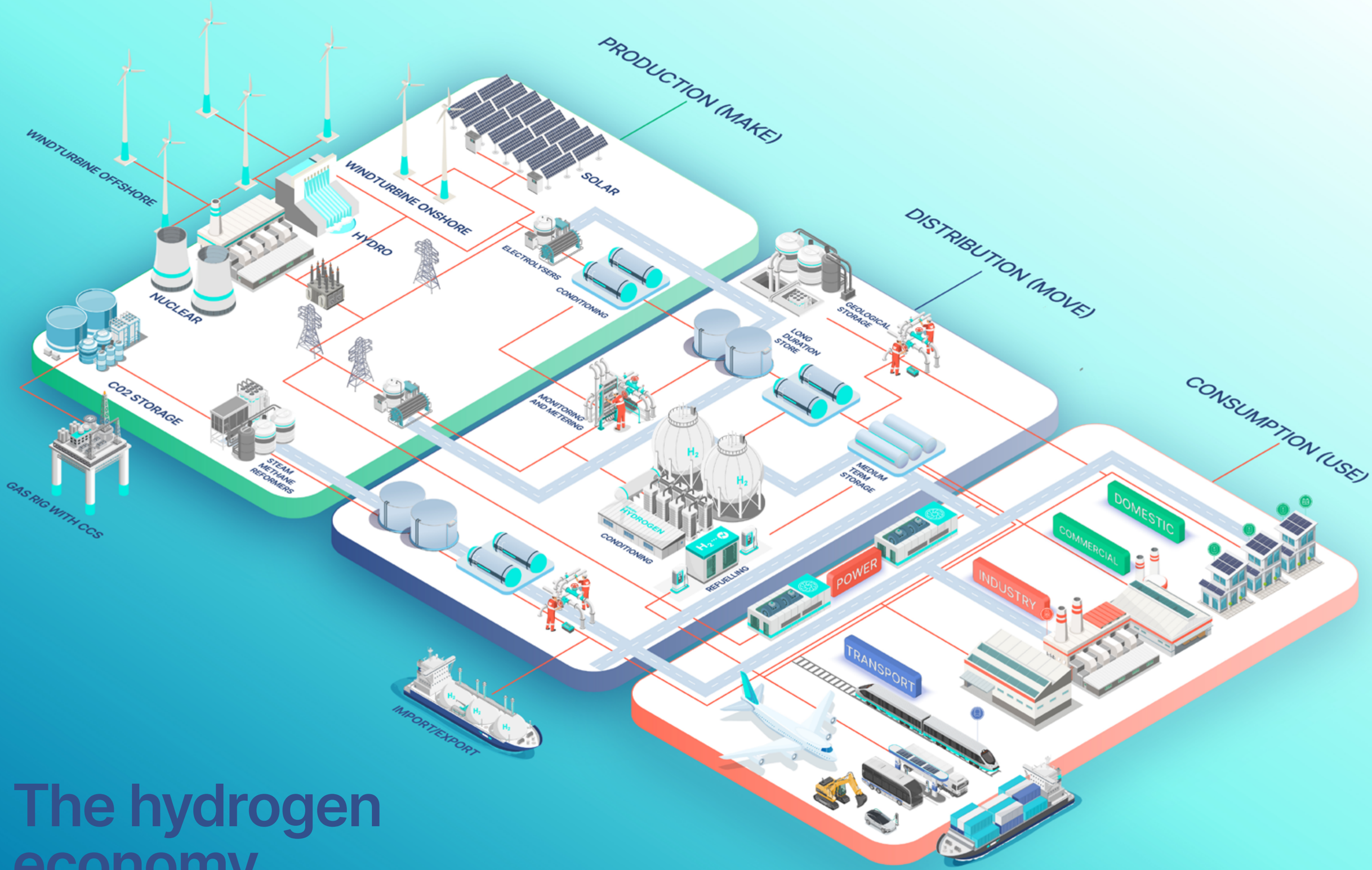
Sustained investment over the next decade will establish the UK's position - boosting public and private investment into key areas to get ahead of international competition. Insights from across industry and key stakeholders have brought clarity to technology requirements and identified four focus areas that represent the greatest potential benefit for the UK:

1. **Production** of hydrogen and conversion into carriers.
2. **Propulsion systems** for transport.
3. **Industrial hydrogen** for feedstock, heat and power.
4. **End-to-end hydrogen** storage.

The next phase of industrial stakeholder engagement will validate the focus areas. This will be supported by detailed analysis to better define the scale of the opportunity and the steps required to secure it for the UK.

The foundations for a domestic hydrogen economy have been established, providing a platform for the UK to capitalise on early mover advantage and seize the global market opportunity. We must now work together to further define the right public-private partnerships that will seize the UK hydrogen innovation opportunity. The routes to success are now clear but the window of opportunity is fast reducing.

We must act now to stake our claim or miss the opportunity.



The hydrogen economy

Scope of report

This report focusses on the opportunity to anchor in the UK, the industrial capability and investment required to drive domestic decarbonisation and secure market share of a successful global hydrogen economy. It considers the emergent nature of the hydrogen economy, the relative immaturity of many critical technologies, and how investing in innovation is essential to anchoring value in the UK.

The insights developed within this document are based upon a first phase of industrial engagement and market analysis. This has involved direct input from more than 250 companies, 12 industry associations and indirect input from the HII partners' extended network and Industrial Advisory Board. The first phase of research, evidence and analysis underpinning this document is contained in four supporting reports:

1. **Hydrogen technology roadmaps:** 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 that explains the analysis behind the hydrogen economy and technology market figures quoted in the ***UK Hydrogen Innovation Opportunity*** and ***Hydrogen technology roadmaps*** reports.

There is often inconsistency in the terminology used to describe the global hydrogen opportunity. For the purposes of this report, the following definitions are used:

- **Hydrogen economy:** The 'end-to-end' value created from hydrogen production, storage, distribution, and use. This includes the direct economic value associated with hydrogen as a fuel or chemical feedstock, hydrogen infrastructure, technologies, products, services, and the indirect economic value created through associated technologies, products and infrastructure.
- **Hydrogen market:** The production of and commercial sale of hydrogen as a fuel or chemical feedstock.
- **Hydrogen infrastructure:** The capital assets that enable production, distribution and consumption of hydrogen such as large-scale hydrogen production plants, hydrogen pipelines and storage and refuelling stations.
- **Hydrogen technology market:** The technologies, products and services directly contributing to the hydrogen economy. For example, the economic activity associated with a hydrogen propulsion system for a heavy goods vehicle (HGV) is captured within the hydrogen technology market but economic activity associated with the remainder of the vehicle is not.
- **Hydrogen technology supply chains:** The companies that design, make, and sell technologies, products, and services to secure a share of the hydrogen technology market.

There are aspects of the hydrogen economy that have been well evidenced and are not explored in detail within this report. These include:

- **Transition to low carbon hydrogen:** There is an existing hydrogen market, but its current production methods create carbon dioxide emissions which limits its adoption [1], [2]. The hydrogen referenced in this document is specifically low carbon hydrogen* [3] that can be produced from new, low emissions processes and will have broader, end-to-end applications as a key part of the energy transition required to reach net zero.
- **Adoption of hydrogen:** The relative merits of hydrogen as a decarbonisation alternative for specific industries or applications [4], [5].
- **Complexity of hydrogen use:** The role of hydrogen in a decarbonised energy system is complex and it is therefore difficult to address the relative merits of individual applications independently. Hydrogen's role is broadly concerned with:
  - **Energy use:** As an alternative energy source for industries that are hard to abate through other technologies or where hydrogen may present a commercial advantage such as HGVs, shipping, aerospace, glass manufacture etc. [6], [7], [8].
  - **Feedstocks:** As a replacement for petrochemical feedstocks into chemical processes, materials, and future foods [9], [10].
  - **Energy balancing:** Utilisation of hydrogen for the purpose of large-scale energy storage, balancing energy grids, addressing renewable energy curtailment issues and as an alternative method for transporting energy as the world transitions to decarbonised energy systems derived from renewable sources [11], [12], [13], [14], [15].

*Low carbon hydrogen

The UK Low Carbon Hydrogen Standard [3] defines what constitutes 'low carbon hydrogen' and sets the requirements that producers are expected to meet for eligible production pathways. These pathways are: electrolysis, fossil gas reforming with CCS, biogenic gas reforming, biomass gasification, waste gasification, and gas splitting producing solid carbon.

1

The hydrogen opportunity

The hydrogen opportunity

There are two primary drivers for UK investment in the hydrogen economy:

1. Decarbonising domestic industries using hydrogen.
2. Industrialising capability to capture a share of the global hydrogen economy.

The UK government and industry are committed to scaling hydrogen production to help decarbonise its domestic industrial base. However, the commitment to building industrial capability for the UK to secure a share of the global hydrogen economy has not been as clear.

The possible scenarios for UK hydrogen use have been explored in supporting report ***Sectors and scenarios***.

Here, consideration has also been given to how UK deployment sits in the context of global adoptions trends and policy commitments from countries also seeking to establish a domestic hydrogen economy. The evolving global hydrogen economy is therefore becoming an increasingly competitive space.

The UK has established strong foundations for a domestic hydrogen economy, positioning the UK as an early mover. This has been achieved through publication and delivery of the *UK hydrogen strategy* [16], the creation of the Hydrogen Delivery Council [17], the Net Zero Research and Innovation framework [18] and most recently the Hydrogen *UK hydrogen supply chain study* [19]. These are supported by 2030 low carbon production ambitions of 10 GW [20], [21] and through targeted support mechanisms such as the Hydrogen Allocation Rounds (HAR) [22], Hydrogen Business Models (HBM) [23] and Net Zero Innovation Portfolio (NZIP) [24]. The Department for Energy Security and Net Zero are also defining the scope of future support mechanisms through the Energy Innovation Needs Assessment [25] and the focus of the Green Industries Growth Accelerator [26].

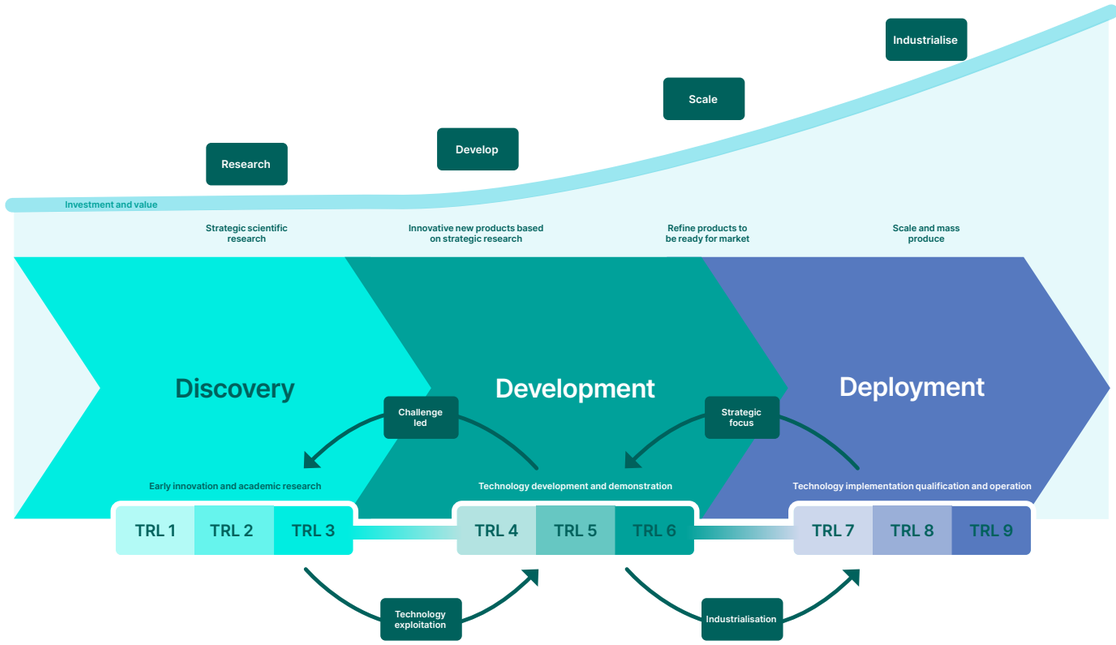
As global momentum builds and competition increases, the UK must consider the full end-to-end opportunity that the hydrogen economy presents or risk falling behind. Existing support mechanisms have become fragmented between government departments and siloed within industrial sectors.

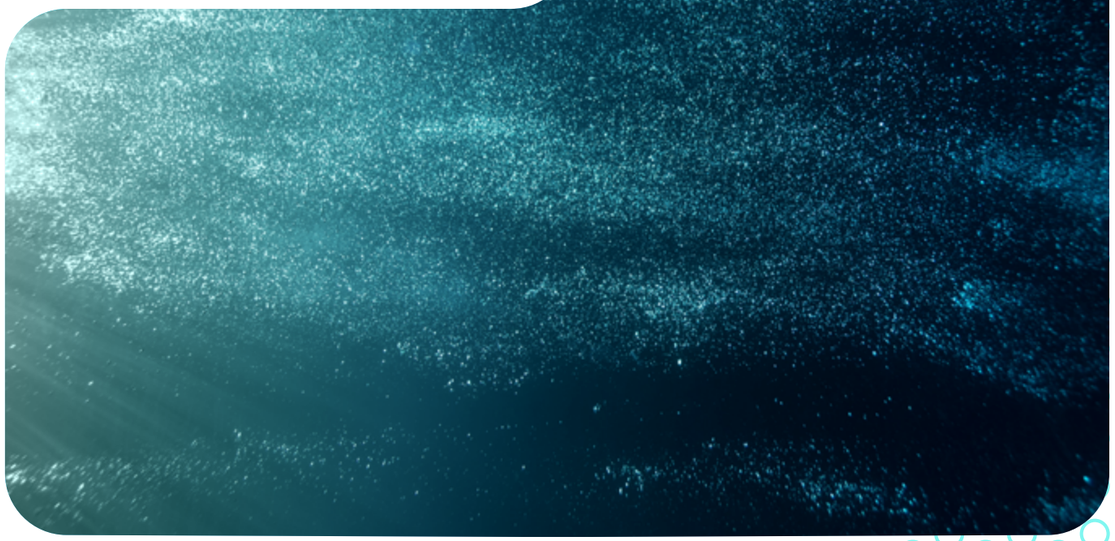
Also, with early support mechanisms focussing on production of hydrogen and its deployment into the UK market, this misses the opportunity for a more holistic approach that considers the longer term investment opportunity for the UK, aligning more closely to the end-to-end nature of the hydrogen economy [27], [28]. Connecting the three phases of discovery, development and deployment will be critical to build competitive UK technology at the scale required (see Figure 1).

As hydrogen is a nascent, technology-driven market, sufficient focus must be given to the development phase of innovation. This is a critical phase where competitive capability is established, market leadership is secured, supply chains are grown, and deep-rooted capital investment is anchored into the domestic economy. Without addressing this, the UK risks becoming reliant on imported technology, products and services from overseas markets. This would result in reduced economic benefit and could restrict access to critical technology as global competition increases. If the UK is to secure a truly leading position, more must be done.

> **The UK has established strong foundations for a domestic hydrogen economy, positioning the UK as an early mover.**

Figure 1. Innovation phases to deliver commercial impact [29], [18], [30]





The global economic context

The global economy is forecast to double from $100tn [31] in 2023 to more than $200tn by 2050 [32]. This report sets the context for the global hydrogen economy to reach $8tn annually by 2050 (4% of the total economy), driven by the critical role hydrogen will play in delivering net zero.

Achieving net zero emissions is a priority for countries around the globe and is increasingly driving industrial transformation. As such many future high growth markets will be those critical to delivering the transition. The industrial transformation required is expected to trigger some $275tn of cumulative investment globally by 2050. At approximately $9.2tn per year [33], this is $3.5tn higher than existing annual replacement investments [34], [35]. Nations that transform their industrial capacity to capitalise on these market opportunities will emerge as leading economies by 2050 and beyond.

By 2050, low carbon hydrogen will drive major contributions to the global economy, impacting every major industrial sector to a varying degree. This will be achieved through the end-to-end system of production (make), distribution and storage (move) and through consumption markets (use). Across the system, it will be used as a source of energy, a low carbon fuel or as a feedstock. It will also be used in many forms such as gaseous, liquid or one of hydrogen's many derivatives (ethanol, methanol, synthetic fuels etc.) [36], [37]. The value derived from this will be rooted in the technologies that make hydrogen work, many of which are not currently available at the scale or maturity required in the global market. This includes electrolysers, steam methane reformers, pipelines, fuel cells, pressure vessels and hydrogen gas turbines to name a few.

The global hydrogen economy

Current forecasts of the global hydrogen market estimate it to be worth between $1.5-2.5tn by 2050 [33], [38], similar in size and shape to today's liquified natural gas market [39]. These estimates typically consider similar scope to the existing natural gas market, focussing primarily on production and storage of hydrogen. As such, they undervalue the additional economic benefits created directly and indirectly across the end-to-end value chain as illustrated in Figure 2.

- **Direct economic value** in the hydrogen economy is derived from hydrogen production, distribution, storage, and use. This includes the hydrogen market, hydrogen technology market and hydrogen infrastructure.
- **Indirect economic value** is derived from the economic contribution of wider industrial activities across production, distribution and consumption markets. For example, airport infrastructure supporting hydrogen aircraft or HGV and ship manufacture.

When both direct and indirect economic benefits are considered, the global hydrogen economy has the potential to be worth $8tn by 2050 (see supporting report ***Techno-economic methodology***).

This represents a significant opportunity for UK businesses, particularly in sectors at risk of declining or stagnating, such as those currently based on fossil fuels. The needs of the hydrogen economy will deliver an opportunity to pivot into new high-growth markets. It could also deliver opportunities to protect existing capabilities in strategically important markets that will be disrupted by the transition to low carbon energy, fuels, or propulsion systems such as the aerospace and automotive industries.

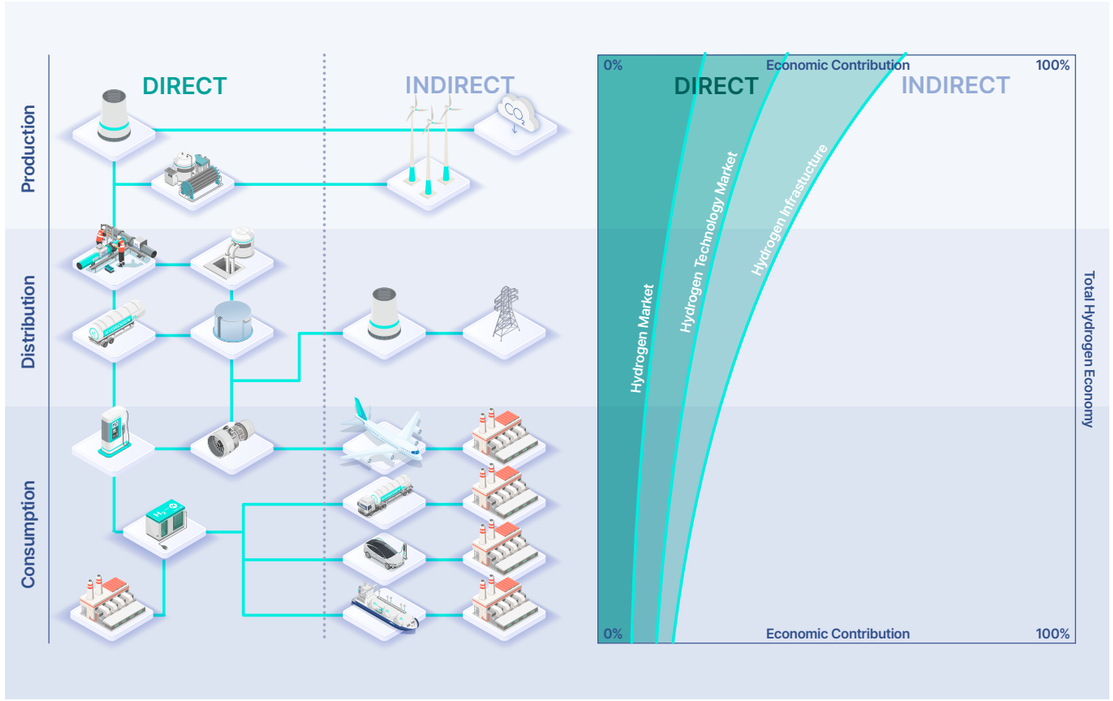
Addressing the UK hydrogen economy alone will be insufficient to build competitive supply chains, leading technology companies or secure the investment required. Without sufficient focus on the global market opportunity and the steps required to connect the key phases of technology innovation (see Figure 1), the UK risks being left behind by its global competitors. As it stands, there is a risk that the investment required to create the hydrogen economy in the UK will flow overseas to procure technology that is not available domestically. This could compound the issue for UK industry further stifling UK growth and global competitiveness.

To address this, the right support mechanisms must be in place that enable UK industry to scale by addressing the global export market opportunity. Taking a broad, end-to-end view

When both direct and indirect economic benefits are considered, the global hydrogen economy has the potential to be worth $8 trillion by 2050.

of the hydrogen economy and the value chains required for it to succeed makes it possible to see where hydrogen technologies will be in demand. This enables identification of critical cross-cutting technologies and the associated innovation challenges required to achieve the scale and supply chain capability required.

Figure 2. The hydrogen economy: direct and indirect contributions



The market growth curve

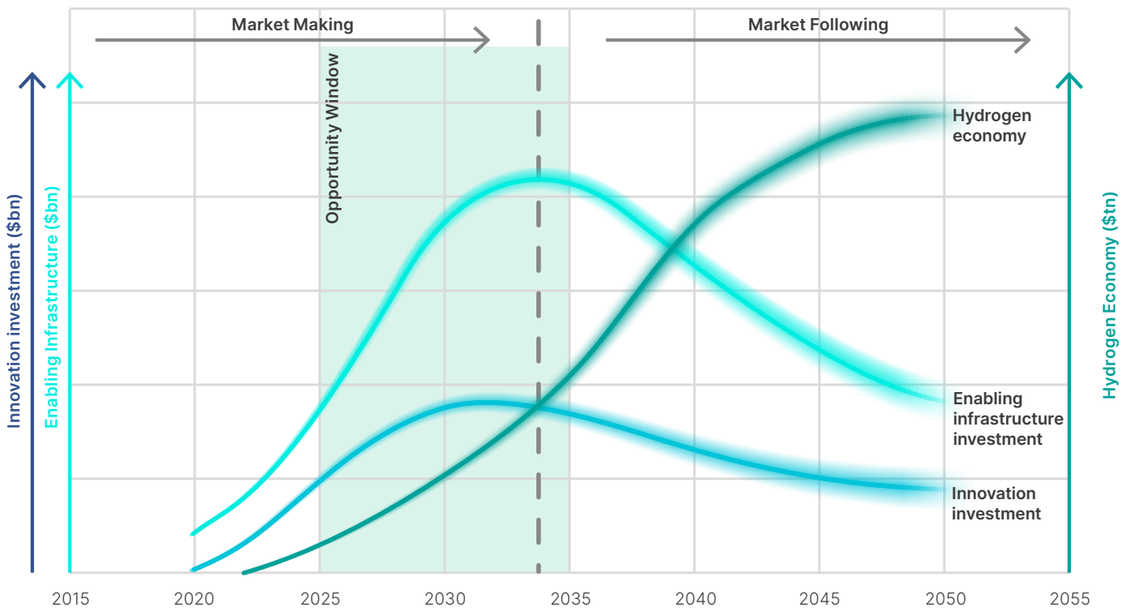
The absolute value of the hydrogen economy in 2050 will depend on a range of factors such as cost competitiveness, technology adoption, regulatory interventions and investment scale. However, we can predict with some confidence the trajectory and phasing of its growth – illustrated in Figure 3 (see also supporting report ***Techno-economic methodology***). The significant features are:

1. **Exponential growth:** The hydrogen economy is expected to grow exponentially until it approaches an inflection point around 2035, with continued slower growth approaching 2050 and beyond – recognising that some markets may still only be at early stages of adoption (e.g. aerospace).

2. **Infrastructure investment:** Adoption of hydrogen relies on investment in and deployment of enabling infrastructure such as pipelines, large scale storage (including geological), refuelling facilities, hydrogen production and manufacturing facilities. This investment is expected to peak before 2035, levelling off at a steady replacement level shortly after 2050.

3. **Innovation investment:** As hydrogen is a nascent market, investment in innovation is essential for the development at pace and scale for required hydrogen technologies, products, and services across the hydrogen economy. Peak innovation investment will precede peak infrastructure investment and is expected before 2035.

Figure 3. Trends in the evolution of the global hydrogen economy



The extent to which a nation secures an influential share of the innovation investment, will determine the share of the infrastructure investment and that will in turn determine the share of the global hydrogen economy. It therefore stands to reason that a strategic focus on innovation will give early mover advantage for nations that are able to invest. With the window of opportunity over the next ten years, failure to put in place the right mechanisms will risk failure to secure global leadership, with the UK relegated to a market follower.

The UK is not alone in laying the foundations to capture market share. International investments are increasing with $570bn of clean hydrogen supply announced globally to 2030 [40] and $3bn of global R&D investment in hydrogen and fuel cells alone in 2023, a figure that is more than doubling each year [41]. If the UK is to stay ahead of international competition a strategic approach to investment in hydrogen innovation must be developed and delivered at pace.

Cross-cutting hydrogen technologies

The first phase of industrial engagement sought consensus on the technologies needed to create an end-to-end hydrogen economy and their associated innovation challenges. These cross-cutting technologies would therefore see demand from multiple sectors, representing sizeable global market opportunities. This phase concluded that nine technology families will drive global demand from international markets and will be critical to delivering domestic decarbonisation.

The forecasted market sizes for these technologies in 2050 can be seen in Figure 4. When aggregated, these constitute the hydrogen technology market which represents an annualised global market of $1tn by 2050 (12% of the global hydrogen economy).

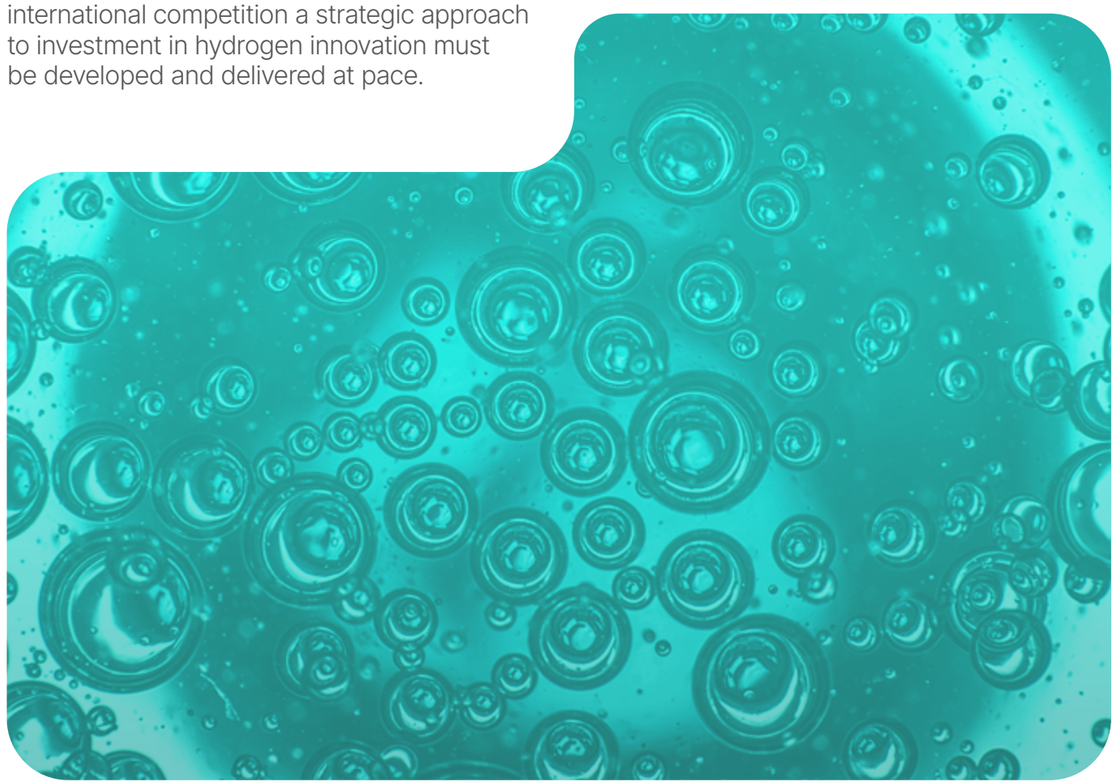
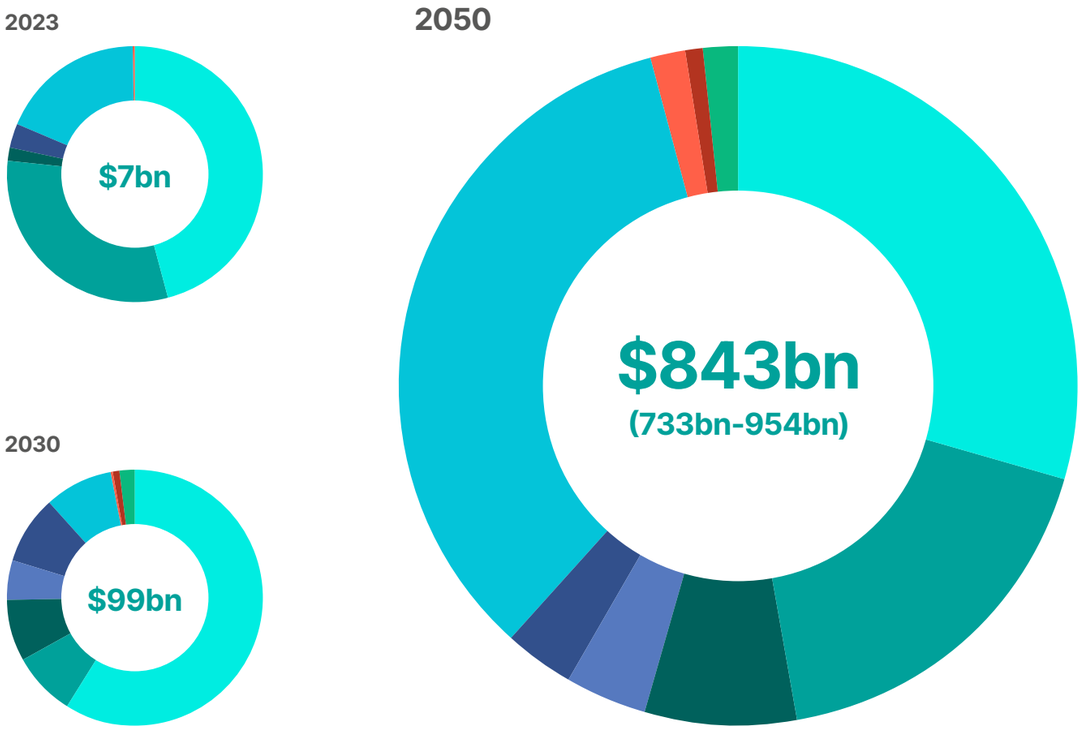


Figure 4. The global hydrogen technology market forecasts split by technology [42]



2050	Production, Distribution & Storage	Consumption - Transport	Consumption - Industry	Totals ($bn)
Production technologies	●	●	●	249
Hydrogen as a feedstock and carriers	●	●	●	288
Storage	●	●	●	62
Propulsion and power generation	●	●	●	150
Heat generation	●	●	●	14
Distribution and control	●	●	●	29
Conditioning	●	●	●	32
Electrical and thermal management	●	●	●	13
Monitoring and metering	●	●	●	6

Key:

● >$80bn ● $10-80bn ● <$10bn

The global hydrogen technology market

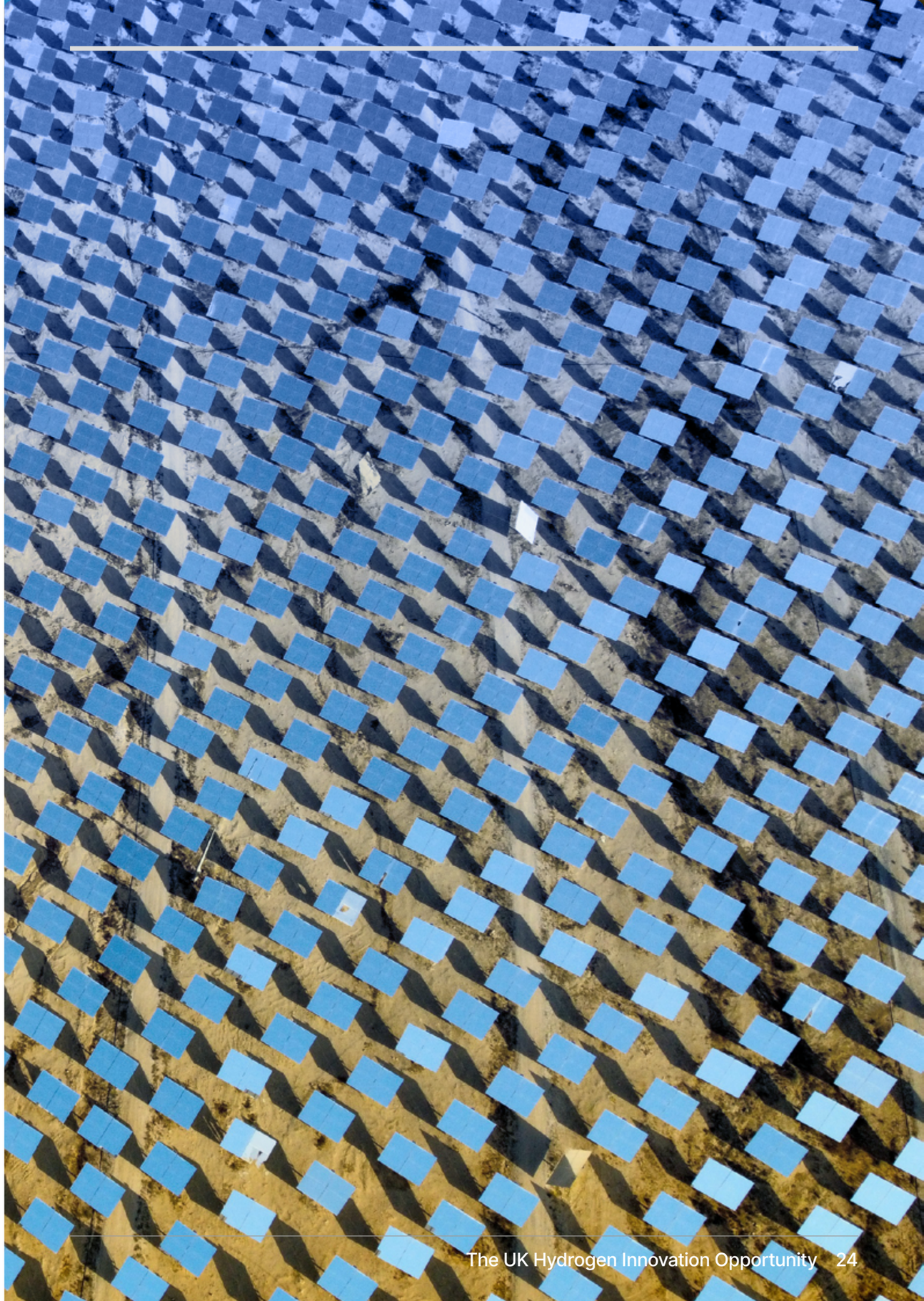
The supporting report, ***Hydrogen technology roadmaps*** provides key focus areas for this capability to be established. In a nascent, technology driven market such as hydrogen, focussing investment on the innovation needed for technology development and deployment is key. This is a critical phase where competitive capability is established, market leadership is secured, supply chains are grown and deep-rooted capital investment is anchored into the domestic economy [28].

Focussing investment on the nine cross-cutting hydrogen technology families* would provide an accelerated route for the UK to secure market share, benefit multiple sectors, and contribute to the UK becoming a global net zero powerhouse. The families are described in detail in the supporting report ***Hydrogen technology roadmaps***. These roadmaps define key innovation challenges and the estimated global market potential for each of the technologies. The UK is also starting from a strong base of industrial capability with an established innovation ecosystem as outlined in supporting report ***UK Capabilities***. Under the right conditions and with the right strategic investments, this can be catalysed for growth.

Aggregating cross-sector demand and technology innovation challenges provides the market intelligence needed to make the right strategic investments for the UK. With the right support mechanisms in place, the UK can accelerate the growth of world-leading companies and globally-competitive supply chains, able to win contracts both in the UK and in overseas markets. This will stimulate a step change in domestic and foreign direct investment into the UK to help UK supply chains scale rapidly, securing an ambitious share of the global market.

***Hydrogen technology families**

- Production technologies
- Hydrogen as a feedstock and carriers
- Propulsion and power generation
- Heat generation
- Storage
- Distribution and control
- Conditioning
- Electrical and thermal management
- Metering and monitoring



The UK addressable hydrogen market

The UK should target a 10%* share of the $1tn global hydrogen technology market - see Figure 5. Targeting this export-led, high growth market would deliver an annual revenue of £46bn by 2050**. This would provide a pathway to secure an equivalent share of the of the global hydrogen economy that could increase the total economic benefit ten-fold. Establishing market leadership in prioritised hydrogen technologies would also deliver wider economic benefits through:

- Protecting UK leadership in existing strategic markets that will undergo transition (e.g. automotive and aerospace).
- Pivoting capabilities from adjacent markets into a high growth market (e.g. oil, gas and refineries).
- Growing innovative supply chain companies with global competitiveness (e.g. electrolytic production, fuel cells).
- Securing resilience*** in UK industry to design and produce technologies that will be required domestically to achieve energy security and reach net zero targets (e.g. electrolysers, hydrogen gas turbines, fuel cells etc – the hydrogen technology families)

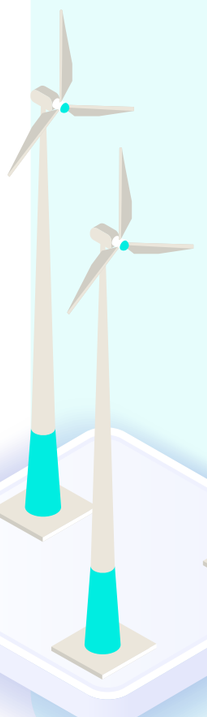
Investing in the UK to secure a share of the hydrogen technology market would also deliver wider socio-economic benefits. High value green jobs would be created across the country, contributing to rebalancing the UK economy as 90% of hydrogen associated job creation is expected be outside of London and the South East, assuming hydrogen technology supply chains follow a similar geographical distribution to the existing UK manufacturing sector [43].

Figure 5. The UK benefits of addressing the global hydrogen technology market

	UK ambition for share of the global hydrogen technology market in 2050	Annual UK revenue in 2050	GVA to UK economy in 2050	Directly employed in hydrogen technology supply chains in 2050
2050 Ambitious	5%	£35bn	£23bn	205k jobs
2050 Transformational	10%	£70bn	£46bn	410k jobs

** Hydrogen technology market forecast is between $733bn-$954bn by 2050.
The UK benefit statement assumes the mid-point value of $843bn for all calculations.

*The UK has a 2% share of global manufacturing (8th in global ranking [46]). In technology driven, high value manufacturing sectors such as aerospace, the UK has captured up to 18% global market share [45].



***National resilience for energy and supply chains

Resilience is the ability of a system to avoid or recover from events including war, natural disasters, equipment failure or human error.

Supply chain resilience depends on supply chain structure and location, the availability of raw materials, trade agreements and barriers, and geopolitical pressures [44].

The resilience of a country's energy system depends upon the availability of energy whether from wind or a fuel like natural gas or hydrogen, the affordability of energy and the acceptability of energy in the context of wider policy considerations (e.g. geopolitical factors).

To be fully energy resilient countries must both have the capability to produce energy and to produce critical equipment, plant and infrastructure. As an example, to have a fully resilient supply of low carbon hydrogen from renewables, the UK must also ensure that it has the capability to design and manufacture electrolysers.

2

Focussing the UK innovation opportunity

Focussing the UK innovation opportunity

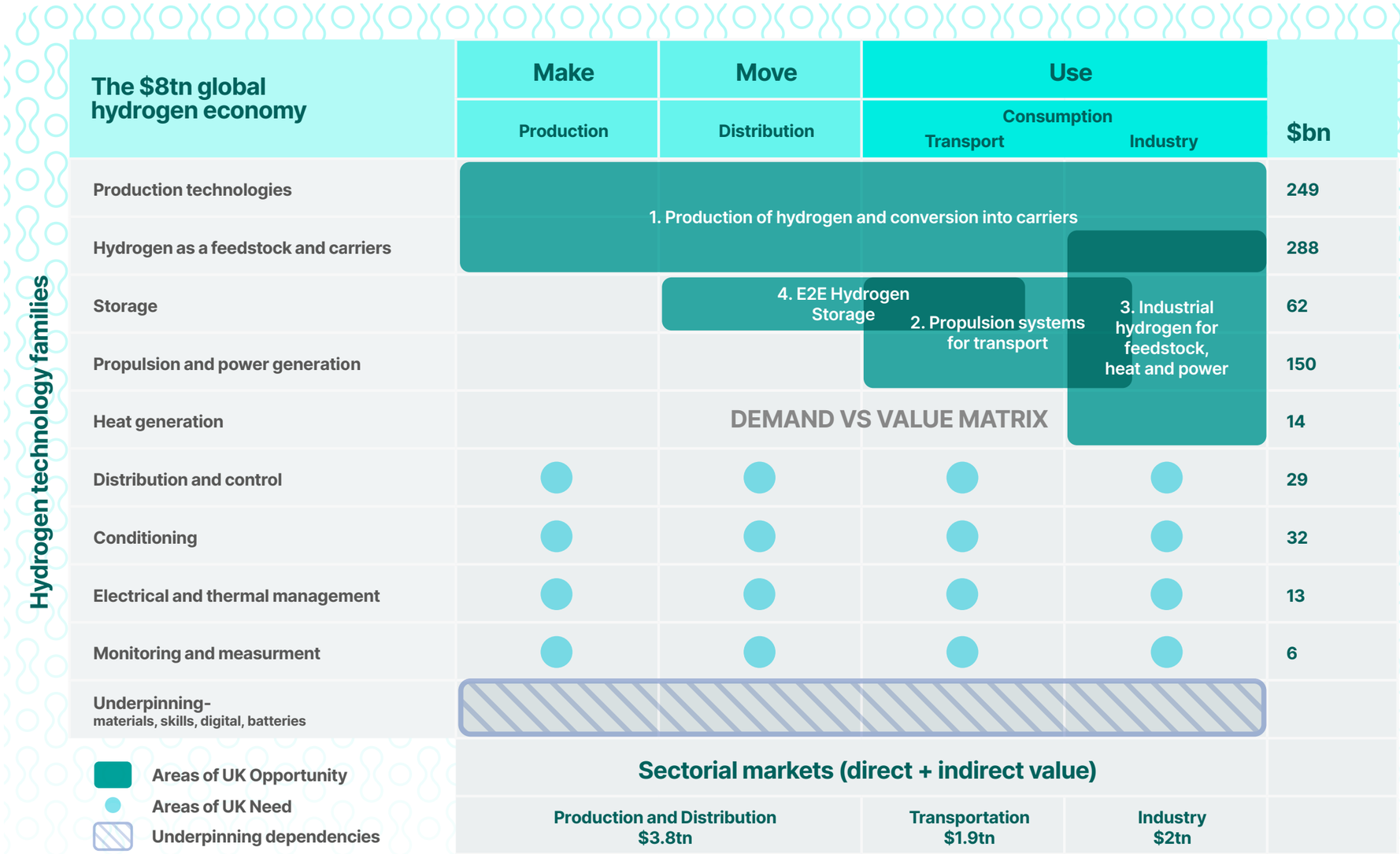
Creating a domestic hydrogen economy in the context of an emergent and rapidly evolving global market is not without challenges. Supply and demand signals lack clarity, creating a myriad of technology and investment challenges across multiple market requirements. This overarching complexity leaves it difficult to navigate both the public and private sectors, meaning areas of convergence and prioritisation are difficult to identify.

To address this, the technology market forecasts (horizontal axis) have been combined with sector focussed forecasts (vertical axis) to determine the key intersections (Figure 6). Corresponding research, evidence and analysis explored in the supporting reports, has highlighted the focus areas that would deliver the biggest impact for the UK:

- **Four strategic areas of opportunity**
- **Four strategic areas of need**
- **Four underpinning dependencies**

The four areas of strategic UK opportunity could provide the primary routes to secure a 10% share in the hydrogen technology market and therefore maximise UK benefit from the broader hydrogen economy – see Figure 6. The next phase of industrial engagement will validate the proposed focus areas, refine the potential scope and determine what mechanisms would need to be in place to secure those opportunities for the UK.

Figure 6. The UK innovation opportunity



Strategic areas of opportunity

These are innovation-led, cross-sector opportunities that offer the highest potential economic benefit and are set to be dynamic global markets. Each involves two or more technology families and two or more sectors.

They address key areas of convergence within the end-to-end hydrogen economy and will require tailored interventions to unlock the full potential of their market-making opportunity.

The strategic areas of opportunity are:

1. Production of hydrogen and conversion into carriers

Focussing on the technologies required to scale up hydrogen production and reduce its cost. Also, the conversion of hydrogen into transportable forms such as pressurised gas, liquid, or its many derivative carriers such as methanol, ammonia, and synthetic fuels.

2. Propulsion systems for transport

Focussing on the propulsion technologies required to enable hydrogen as an alternative fuel across the transportation sector, with potential crossover into power generation due to the cross-sector application of hydrogen turbines and remote power generation using fuel cells.

3. Industrial hydrogen for feedstock, heat and power

Focussing on the technologies required to support decarbonisation of heavy industrial sectors such as steel, aluminium and glass. Also considering its use for industrial space heating or power for industrial purposes, along with its use as feedstock for chemicals or pharmaceuticals.

4. End-to-end hydrogen storage

Focussing on the technologies required to store hydrogen at various stages across the end-to-end of the hydrogen economy. This will include large scale storage for potential grid support or import bunkering to smaller scale refuelling stations and containers to transport hydrogen in discrete volumes.

Strategic areas of need

These are fundamental supply chain capabilities that will support the global and domestic hydrogen economies, but with relatively low individual market potential by 2050. However, without access to this supply chain capability the strategic areas of opportunity will be challenging to address. Investing in development in these areas is essential to establishing a sovereign hydrogen economy. A failure to do so risks the UK becoming dependent on imported technologies, exposed to shortfalls in supply and rising costs. This would both stifle the development of the UK hydrogen economy and act as a brake on achieving net zero targets. Indeed, some UK hydrogen programmes are already experiencing delays resulting from challenges accessing technologies from domestic and international supply chains in these areas.

The UK strategic areas of need are:

1. **Distribution and control**
   Components required to safely distribute and deliver hydrogen, covering both infrastructure and on-vehicle.
2. **Conditioning**
   Preparation of hydrogen for distribution and use, including compression, liquification and purification.
3. **Electrical / thermal management**
   Electrical and thermal management required for hydrogen across end-to-end.
4. **Monitoring and measurement**
   Using sensors and monitoring systems to ensure the safe and efficient operation of hydrogen systems.

Underpinning dependencies

Two of the underpinning dependencies, materials and digital, are technology driven as identified in ***Hydrogen technology roadmaps*** but all four are areas that will be shaped by broader requirements than just hydrogen. Establishing the right mechanisms will be key to ensure the needs of the hydrogen economy are recognised and delivered. Connectivity to the other priority areas for the UK will also be important in building a resilient, hydrogen economy:

1. **Materials**
   Materials for hydrogen will be required to address specific issues such as hydrogen embrittlement and permeation, or to achieve significant reductions in cost and improved circularity. The Henry Royce Institute's landscape report *Materials for End-to-End Hydrogen* and its Hydrogen Accelerator are seeking to address this challenge [47].

3. **Skills**
   The emergent nature of the hydrogen economy means there is a shortage of qualified and experienced professionals across the end-to-end value chain. Innovation provides a mechanism of 'learning through doing' but more formal routes for workforce transformation will be required for hydrogen. The Hydrogen Skills Alliance and Green Skills Taskforce are seeking to address this challenge [49].

2. **Digital**
   UK industry has global strengths in high value-add areas such as advanced manufacturing and technology. Digital technology will provide a differentiator for UK businesses and give pathways to drive down the cost curve of hydrogen technologies in the design and manufacturing phases. Digital systems will also support energy system modelling and design along with new ways to manage, measure, control and validate hydrogen [48].

4. **Batteries**
   Where hydrogen is converted into electricity using technologies such as fuel cells, battery technology is required. For example, hydrogen fuel cells will require battery technology to be efficient, low weight and sustainable. The UK Battery Strategy and Faraday Challenge will be key for the UK to achieve this domestically, supporting both electrification and hydrogen deployment needs [50], [51].

Identifying adaptive interventions

To maximise the economic impact of the global hydrogen economy and secure an ambitious UK market share, the right outcomes need to be understood and the right intervention must be determined.

The first phase of industrial engagement highlighted three priorities that should be considered for any intervention to support the hydrogen economy and develop world-leading capability in UK technology supply chains:

1. **Focus on business-led innovation** that addresses both the domestic and global markets.
2. **Support market readiness** and accelerate the time to market for innovation from technology development through to deployment.
3. **Reduce fragmentation** and development in silos to ensure shared learning and balance between regional clusters and national priorities.

It is important to create an intervention that is fit for purpose and draws on the relative successes of initiatives that the UK has historically deployed. These form the context for four broad categories:

1. **Pervasive challenge focussed programmes**
   Large interventions that target the end-to-end requirements of a particular grand challenge. Examples: Faraday Battery Challenge [51], Made Smarter [48], Industrial Decarbonisation challenge [52], Transforming Foundation Industries Challenge [53], Transforming Construction Challenge [54].
2. **Targeted intervention focussed programmes**
   Targeted intervention programmes that focus on a specific outcome or area. Examples: Fit for Nuclear (supply chain) [55], Advanced Propulsion Centre UK (APC) [56], Aerospace Technology Institute (ATI) [57], Net Zero Technology Centre (NZTC) [58], Construction Innovation Hub [59].
3. **Enabling infrastructure and assets**
   Specific provision of research or innovation assets that enable industry to access capability, people or equipment within the UK market. Examples: The Catapult Network [60], National Physical Laboratory (NPL) [61], Glass Futures [62], TWI [63], Henry Royce Institute [64], Medicines Manufacturing Innovation Centre (pharmaceutical manufacturing) [65].
4. **General support mechanisms**
   Untargeted funding support that encourages collaboration in research and innovation in the UK market. Examples: Business support [66], Innovate UK Smart grants [67].

The priority for the next phase of industry engagement will be to consider how strategic interventions will be tailored to address the opportunities and how they will be delivered. It will be important to consider how to build sufficient capacity to be adaptive and responsive to changing market conditions. This will be key to ensure the UK remains at the forefront, in the context of a rapidly evolving global hydrogen economy.

3

Conclusion and next steps

Conclusion and next steps

Hydrogen is now recognised as playing a critical role in helping the world reach net zero by 2050 with the potential to deliver $8tn to the global economy. Its versatility and high calorific value will provide options to deliver energy into many sectors that are challenging to decarbonise.

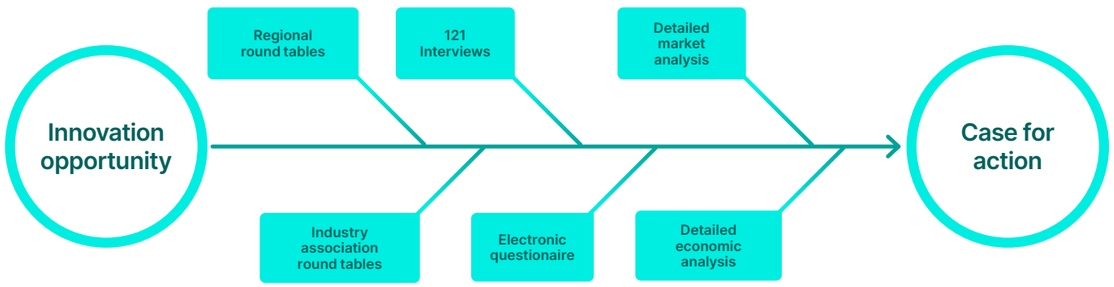
This report has considered a broad economic model that represents the true end-to-end value that hydrogen will deliver – covering the intersection between the sectorial and cross-cutting technology markets. This has identified four strategic areas of opportunity that represent the biggest potential for UK industry and will provide export-led, high growth markets for domestic companies and supply chains.

The UK must use its domestic hydrogen deployment to stimulate early supply chain growth and be positioned for a global export market. Tailoring the right interventions will allow industry, government and academia to converge, focus investment and deliver the high economic growth opportunities that the UK needs. This will provide a pathway to become a genuine world leader, shaping the global market, and ensuring that hydrogen 'works' for the UK. The next phase of industrial engagement will validate the focus areas identified and undertake more detailed analysis to clearly define the scale of the opportunity they represent (see Figure 7). This will enable more specificity in the scope and articulation of the targeted outcomes along with the tailored interventions required to secure them. This will also be supported by early indications of the investment potential from both industry and the investment market against the key focus areas.

A second report entitled '***Hydrogen Innovation: The Case for Action***' will be published following this engagement phase and will contain the key recommendations required to maximise the UK benefit from the hydrogen economy within the expected ten-year window.

The UK has been at the forefront of key foundational investments and has put in place the policy mechanisms to establish an early footing. This provides a platform for the UK to capitalise on early mover advantage. However, with global competition increasing, the innovation imperative is clear and the need for strategic intervention is critical. Moving to the next phase, the UK must harness its full innovation pedigree to unlock the value that the hydrogen economy presents.

Figure 7. Phase 2 Industrial Engagement



We must now work together to further define the right public-private partnerships to accelerate our activities and secure the benefits of the hydrogen economy.

The routes to success are now clear but the window of opportunity is fast reducing.

Now is the time to unlock the UK hydrogen innovation opportunity.

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