Hydrogen Innovation Initiative

The UK Hydrogen Innovation Opportunity

Sectors and scenarios

September 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.

This report explores the UK's sector needs and different pathways for future hydrogen uptake. It has been produced as a supporting report to the *UK Hydrogen Innovation Opportunity.*

Contents

Report overview

Global demand for hydrogen is expected to increase significantly as we progress to net zero by 2050. For the UK, hydrogen will be key in reaching its net zero targets and represents significant innovation and technology development opportunities for companies and supply chains to address domestic and global market needs. It has the potential to play a role across all future demand sectors (industry; transport; power generation; and heating) to varying extents. Globally, the use of hydrogen will vary from country to country and be highly dependent on national policy choices, energy system opportunities and challenges.

In this context the Hydrogen Innovation Initiative (HII) has developed a series of UK specific energy system scenarios, with varying estimates of hydrogen production and use in the UK, using whole energy system modelling to draw key insights on what might be required to deliver a competitive hydrogen value chain. These scenarios explored a range of possible, but distinct, pathways, distinguished by different policy choices and characteristics of the hydrogen value chain such as technology deployment rates, infrastructure and demand needs. In addition, a global analysis was conducted to explore targets and ambitions, hydrogen demand forecasts, and sector technology needs, to establish links in technology development and sector needs between the UK and other countries.

The key findings from this research are:

- **Investment in hydrogen technology is urgent.** UK annual demand for hydrogen could reach almost 300 TWh by 2050, equivalent to the UK's electricity demand today. This means we need to build a strong supply chain for hydrogen in just 25 years. Investment to drive down the costs of and derisk hydrogen technologies can help address this challenge, and is key to reduce longer term costs and increase investment certainty. This is especially true where there are limited decarbonisation options and across the hard-to-decarbonise sectors. This needs to actively consider UK needs and global market opportunities and is particularly important during the hydrogen industry's early development phase, as any individual nation is unlikely to have sufficient market demand to support the scale and cost requirements of a self-sufficient domestic supply chain.
- **Demand for hydrogen could outstrip current production targets by 2030.** Deployment and demand for hydrogen in several of the scenarios exceeded the 2030 production capacity the UK Government has targeted (10 GW). This need for earlier adoption is driven by the 2050 net zero target. Accelerating early deployment of hydrogen technologies and their supply chains (across production, distribution, storage and consumption) in the late 2020's and early 2030's is therefore key for the UK to achieve net zero by 2050. This reinforces the need to progressively build-out production capacity, in tandem with demand and associated supply chains, to enable the UK to capitalise on the opportunity.
- **Hydrogen is needed to support decarbonisation of multiple sectors.** Hydrogen demand is not expected to be dominated by any single sector, illustrating its versatility. However, there is a consensus forming that deployment of hydrogen can most effectively develop and propagate from the forward-thinking industrial clusters in the UK, and overseas.
- **A variety of hydrogen production options are required.** Multiple low carbon hydrogen production pathways are expected to be required, using electricity, natural gas and biomass as feedstocks. For the UK to achieve net zero negative emissions technologies are expected to play an important role. Hydrogen produced via biomass gasification with carbon capture and storage (hydrogen BECCS) has the potential to create a carbon negative hydrogen energy vector with significant potential system value as part of the whole energy system solution, helping to offset emissions from other hard-to-abate sectors such as industry, aviation, and agriculture. The mix and scale of hydrogen production solutions will be influenced by energy system design and technology development potential.
- **The UK could and should play a role in global hydrogen technology development.** Hydrogen is expected to be a globally traded commodity. This would create a demand for hydrogen related technologies and the supply chains required to scale up and deliver it at pace. Whilst the technology mixes for the UK and other nations remain uncertain, and each country has its own timescales and challenges to contend with, the UK has the potential and opportunity to carve out a role within the global hydrogen technology supply chain.

The global hydrogen technology market has been estimated to be worth up to $1tn by 2050 (*UK Hydrogen Innovation Initiative Opportunity Report*). Analysis for this report reinforces the important potential role of hydrogen in the UK delivering on its net zero commitments and realising global economic opportunities. The UK has a role to play, in developing and demonstrating hydrogen technologies at an industrial scale as part of integrated decarbonised energy systems as well as realising the opportunities for creating global technology development partnerships. With many nations seeking to capitalise on the economic growth potential of hydrogen, and some aggressively pursuing a leadership position, the time to act is now if the UK is to realise its ambition.

Introduction

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***
   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 (this report)***
   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 explores how hydrogen could be taken up in the UK, and how this in turn translates to each sector from both global and UK perspectives to understand the practical implications of global and UK targets and projections on hydrogen innovation opportunities:

- **Assessing demand for hydrogen** sets out the context and the approach taken in the assessment of global and UK sector hydrogen needs including the development of specific UK scenarios for hydrogen deployment and innovation across the energy system and supply chain.
- **Key insights** discusses the insights and an overview of the outputs from the implementation of the UK deployment scenarios in whole energy system modelling.
- **Hydrogen production, storage and distribution and demand** explore these areas in more detail, setting out the current state and potential trajectories for hydrogen in each sector, both globally and in the UK, up to 2050.

Assessing demand for hydrogen

Hydrogen is projected to be taken up in great quantities globally and will be key to the UK achieving its net zero targets. The International Energy Agency estimates that 17,500 TWh of hydrogen will be needed annually by 2050 to meet global net zero targets [1]. This demand represents a potential global hydrogen economy worth $8tn by 2050 (see supporting report **Techno-economic methodology**).

Each country has their own resource, political and technical challenges, and timescales to achieve net zero. Many are taking the lead in certain "challenge" areas with some aggressively pursuing hydrogen. USA, Japan, Germany, Canada, South Korea, China, Saudi Arabia, and Australia are large investors into the sector. Hydrogen is therefore likely to become a globally traded commodity with notable export-oriented countries being Morocco, Australia, Iceland, and Saudi Arabia with import-oriented countries being Japan, Germany, and Belgium.

UK demand for hydrogen today is driven by existing industrial uses but very little of this is produced by low carbon means. Hydrogen usage is estimated to increase over the coming decades to deliver net zero. However, the amount of hydrogen needed could vary quite significantly with large, quoted ranges between 180 and 350 TWh (see Figure 1). To put this into perspective the UK's electricity demand in 2021 was 334.2 TWh with well-established production methods which have slowly transitioned by adding new electricity production technologies to existing and slowly evolving infrastructure.

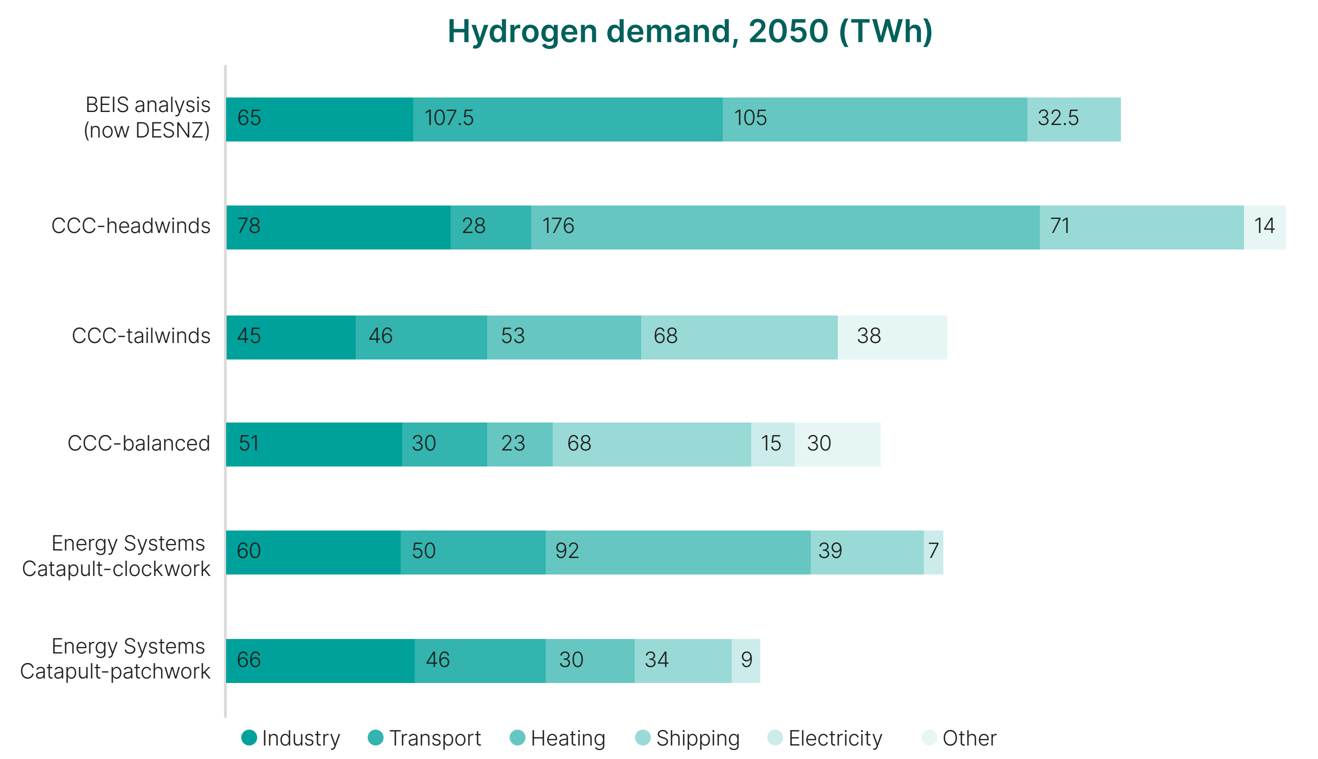
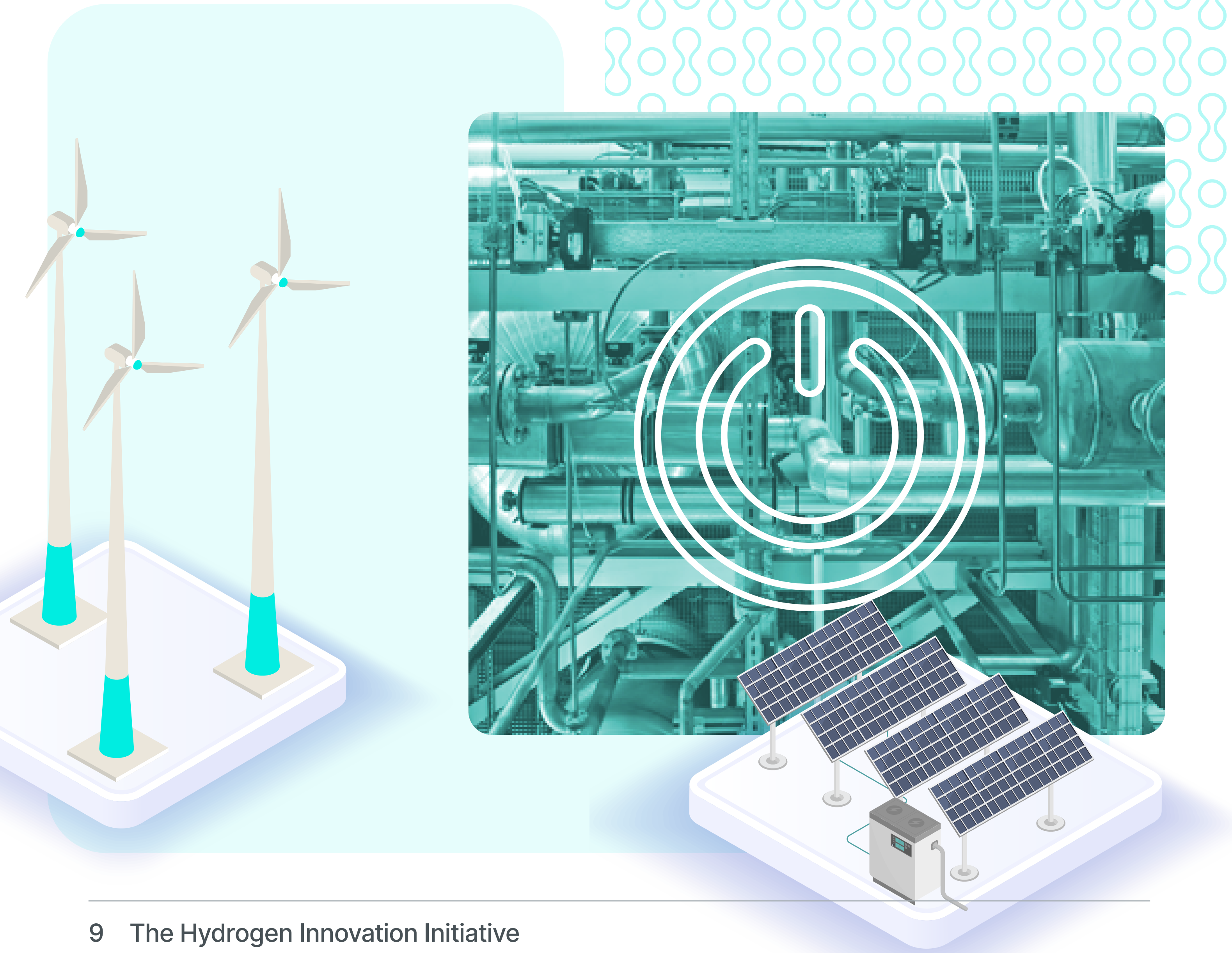


Figure 1. Estimated UK hydrogen demand, DESNZ [13], CCC [4] and Energy Systems Catapult scenarios

Hydrogen has the potential to play a role in all relevant UK demand sectors (industry, transport, power generation and domestic and commercial heating) to varying extents. Globally this will vary from country to country and be highly dependent on policy choices and energy system challenges. To explore and refine estimates of how hydrogen might be taken up in the UK, UK specific scenarios and whole energy systems modelling was conducted. A global analysis was conducted to explore targets and ambitions, hydrogen demand forecasts and sector technology needs, so as to establish links in technology development and sector needs with the UK and other countries.

> **"The task being faced in the UK is to build an energy supply chain for hydrogen as large as today's electricity system, from virtually nothing, in just 25 years.**



Global hydrogen demand methodology

A range of sources have been analysed to build an understanding of the global context and potential demand for hydrogen and hydrogen technologies across different sectors. This is split into three elements:

1. **Targets and ambitions**
   - **a.** Sources include countries' and regions' hydrogen and net zero strategies, International Energy Agency and International Renewable Energy Agency scenarios.
   - **b.** For some sectors, targets have been set via specific international bodies, such as the International Maritime Organisation.
2. **Demand forecasts**
   - **a.** Targets and ambitions may not be achieved in practice, so market analysis forecasts and industrial insights are also needed to build a full understanding of the global context and potential demand for hydrogen.
3. **Sector technology needs**
   - **a.** Key technology requirements for each sector have been derived predominantly from market analysis forecasts and industrial insights.
   - **b.** The Advanced Propulsion Centre and Aerospace Technology Institute have recently published reports regarding hydrogen technology requirements for road and aviation transport respectively, which have also been referenced.

Alongside these sources, industry experts were engaged to validate understanding of each sector and global trends.

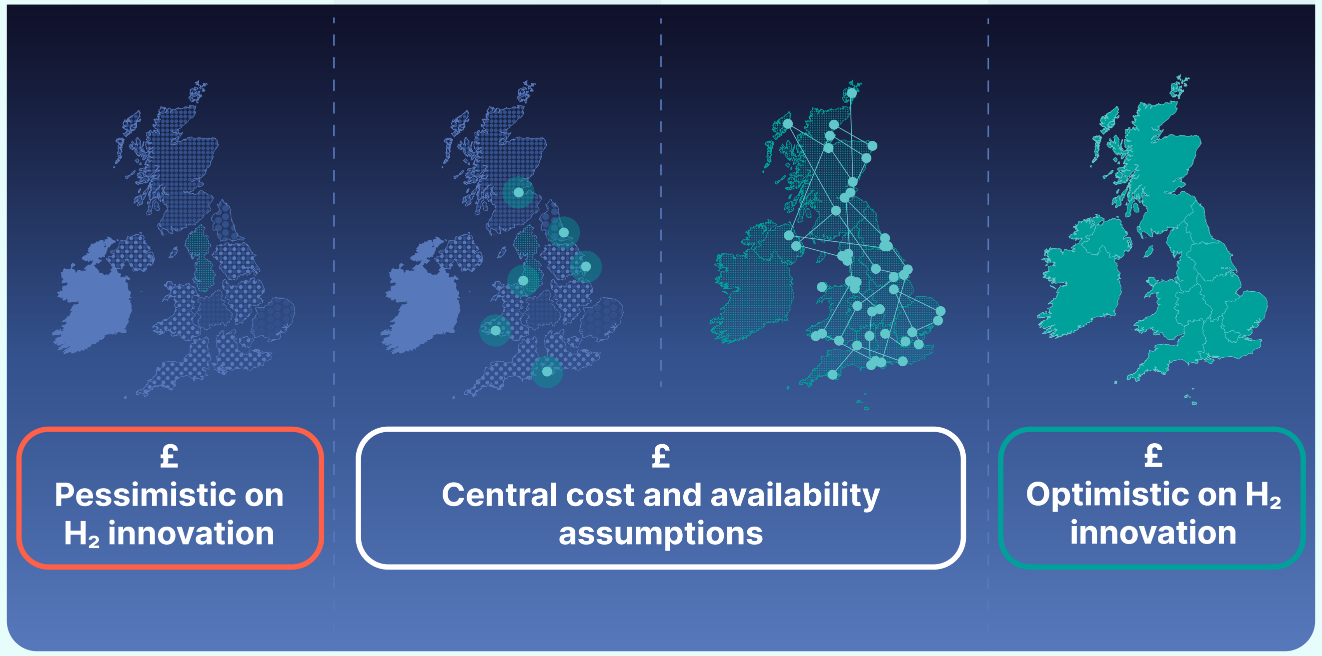
UK hydrogen demand methodology

To refine the demand estimations for hydrogen in the UK, the technologies and supply chains required data representations of some demand sectors and hydrogen technologies to be significantly improved. HII developed new datasets and representations across parts of the energy system which has been used in whole energy systems modelling to explore the ranges of possible hydrogen technology deployment using scenarios. These scenarios explore a range of possible, but distinct, pathways, distinguished by different policy choices and technological characteristics focused on the hydrogen value chain.

Four scenarios were developed and explored to test different future views of the UK hydrogen landscape. Each depicts possible worlds principally defined by a combination of how coordination around hydrogen technology innovation is delivered and the degree to which that innovation can be delivered (see Figure 2). At one extreme, hydrogen pessimism portrays a world where innovation in hydrogen technology stalls and there is a delay in reaching commercial viability of five more years beyond what we expect today. Hydrogen optimism, by contrast, assumes hydrogen innovation progresses at pace and commercial viability is reached five years ahead of what is expected today.

Figure 2. Overview of scenarios

Hydrogen pessimism	Industrial cluster propagation	Policy led	Hydrogen optimism
Hydrogen is viewed with “pessimism” in the UK with the investment and support to commercialise not forthcoming. Hydrogen that is deployed is locally or regionally focused.	Major hydrogen deployment centered around industrial clusters. Small/minimal production allowed elsewhere. Transport hubs in and around industrial clusters. Hydrogen domestic heating restricted to industrial cluster regions	Fully decarbonised power system by 2035. Direction of policies such as: Net Zero Strategy; Powering up Britain; Energy Security Strategy; Hydrogen Strategy. Includes an interpretation of the hydrogen production business models.	Hydrogen is viewed with “optimism” in the UK and globally driving heavy innovation investment bringing forward the expected commercial availability of technologies. Strong national coordination.



Forming the approach to a robust analysis for hydrogen demand involves the exploration of several potential development pathways for decarbonisation. Understanding current emissions and the progress of recent UK projects provides a solid foundation to begin, supported by reliable data and costings. However, as we look further ahead, the certainty diminishes, making it more challenging to discern the most effective strategies. Scenarios are developed to test potential decarbonisation pathways and the role of different energy vectors. They are not expected to be equi-probable; indeed, some are explored to better define the difficulties of deployment along certain pathways to screen them and to inform decision making.

Each of the scenarios tested or stressed different aspects of the energy system and individual technologies, such as:

- A fully decarbonised power system by 2035 – consistent across all scenarios
- Government policy commitments such as the Net Zero Strategy, Powering Up Britain, British Energy Security Strategy.
- Hydrogen strategy – implementing and testing the UK government commitments.
- Technology availability – when technologies might become commercially available.
- Interpreting and simulating the hydrogen business models.
- Variations in technology capital cost – the forecast cost reduction curves towards commercialisation and the forecast fully commercialised costs. Hydrogen optimism considers large investments accelerating hydrogen technology development across the system bringing forward technology commercial availability while hydrogen pessimism does the opposite delaying the commercial availability.
- Locational aspects – considering infrastructure and place-based location of technology deployment.

Traditionally scenarios include behavioural change characteristics, population change and others, but these have remained constant to assess the technical supply chain and policy implications. Each scenario aims to achieve net zero and the interim carbon budget targets set by the UK government. They also aim to portray sector ambitions or decisions where they have already been made.

Throughout each scenario many variables were adjusted or constrained which shape the scenarios (see Figure 3). Outputs from the modelled scenarios provide perspective on: the potential UK uptake of technologies; the variation between scenarios; their importance for reaching net zero; energy security and resilience in the UK (see Figure 2).

Scenarios were refined in consultation with stakeholders (government and industry), to further improve granularity.

Figure 3. Overview of energy systems modelling

Energy systems modelling environment

HII modelling has explored the emissions, energy use and cost of decarbonisation across the scenarios. ESME (Energy Systems Modelling Environment) was originally developed to evaluate the role of innovation in UK energy system decarbonisation, from energy resources and conversion through to end use in buildings, transport and industry. It is used by Energy Systems Catapult, Government, industry, the Climate Change Committee (CCC) and academia.

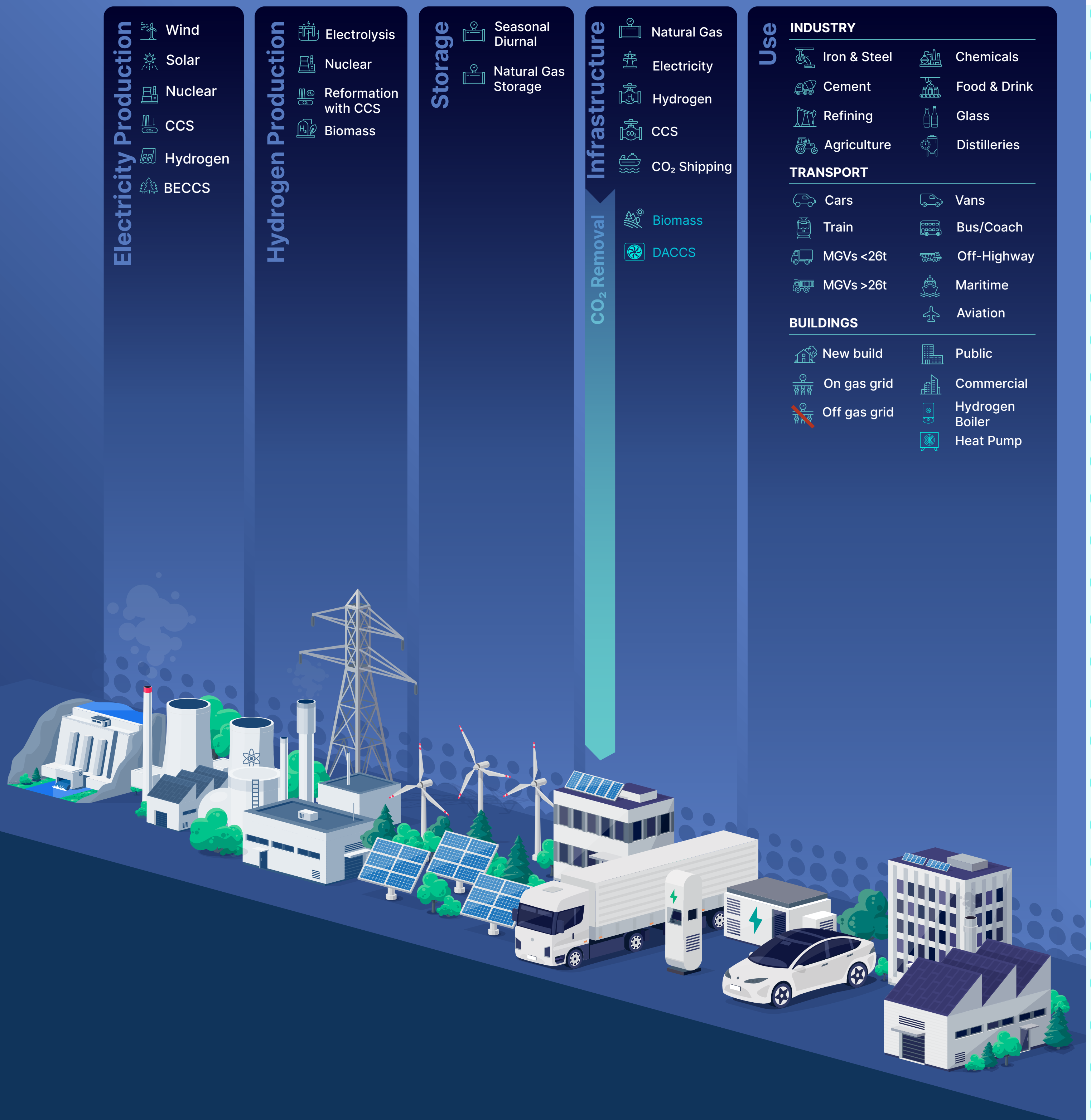
ESME is an optimisation model and finds the least-cost combination of energy resources and technologies that satisfy UK energy service demands along the pathway to 2050. Constraints include emissions targets, resource availability and technology deployment rates, as well as operational factors that ensure adequate system capacity and flexibility. It is focussed on the physical components of such a system – infrastructure, energy flows and associated costs – and does not look at other layers of the system such as commercial aspects or communications between actors.

Importantly, ESME includes a multi-regional UK representation and can assess the infrastructure needed to join up resources, technologies and demands across the country. This includes transmission and distribution networks for electricity and gas, and pipelines and storage for carbon dioxide.

The philosophy within ESME is of modelling the UK as an energy island. Whilst ESME considers energy imports and exports, it does not rely on them (for balancing, etc.) when indigenous sources are not available.

Policy-neutrality is a fundamental principle when using scenarios built in ESME, wherein minimal second-guessing of how policy could de-risk investment in the future takes place. However, within the HII scenarios specific policy choices and directions are built into certain assumptions — one example being hydrogen production targets.

Across the scenarios variations in technology availability, cost (optimistic vs pessimistic cost reduction timelines), locational availability, availability timing, technology propagation and policy measures were tested.



Key insights

The scenarios show the annual demand for hydrogen in the UK could reach almost 300 TWh by 2050, equivalent to the UK's electricity demand today [2] (see Figure 4). **In all scenarios, even with a pessimistic view, hydrogen will play a significant role across the energy system in the UK achieving net zero.** However, the exact scale of this role will depend on policy choices, investment, and technology developments.

> **The annual demand for hydrogen in the UK could reach almost 300 TWh by 2050, equivalent to the UK's electricity demand today.**

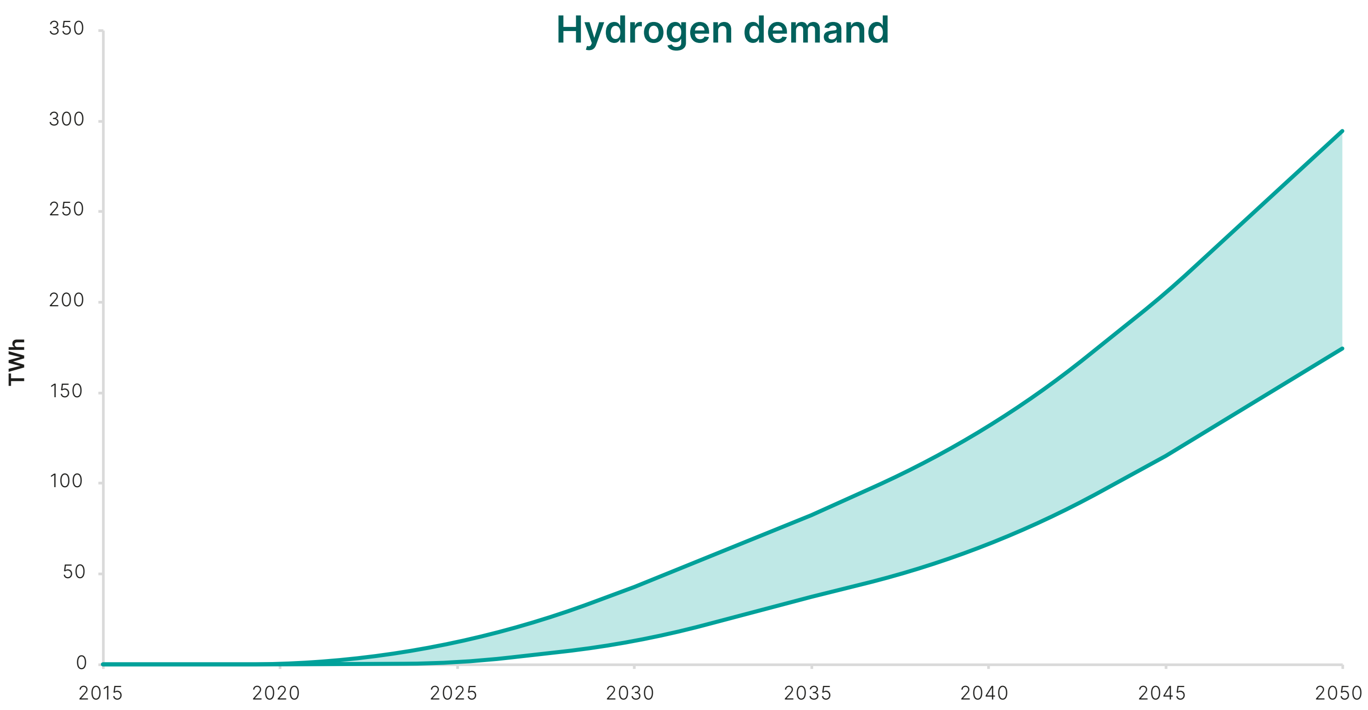


Figure 4. Hydrogen demand range across the scenarios modelled. Across the scenarios, the amount of hydrogen demanded varies within the range shown from around 12-42 TWh in 2030 to 175-295 TWh in 2050.

- Deployment of hydrogen and hydrogen technologies is driven by the role hydrogen plays as part of the whole energy system solution.
- Providing investment to drive down the costs of hydrogen technologies is key to reduce long-term costs, derisk investments and increase certainty. Demand for hydrogen across the system is driven, in most cases, by the solutions available for each sector to decarbonise and by how well these solutions apply to each sector, the cost (both OPEX and CAPEX) and the technology availability including infrastructure. This is especially true where there are limited decarbonisation options and across the hard to decarbonise sectors, i.e., aviation, manufacturing industries, heavy duty vehicles and maritime.
- **In all scenarios, demand for hydrogen outstrips the current UK government production commitment by 2030.** To meet demand, required production capacities across the scenarios are 10.8 to 16 GW in 2030 and 28.4 to 41.8 GW in 2050. **The drive for earlier adoption of hydrogen in all scenarios beyond existing targets is driven by the 2050 net zero target. This reinforces the need to progressively build out capacity from now to 2050.**
- Demand for hydrogen is not dominated by any single sector, illustrating its versatility. However, key decisions remain which could have a significant impact on how much each sector contributes to that demand; in particular the decision around hydrogen for home heating which is expected in 2026 [3].
  - Hydrogen demand for home heating varies marginally across the scenarios, apart from the pessimism scenario where it was assumed the decision in 2026 was not to proceed. The industrial cluster propagation scenario restricts availability of hydrogen for home heating to in and around industrial cluster regions but has similar levels of deployment to the policy led scenario. However, restricting location availability of hydrogen heating has a huge impact on the hydrogen transmission and distribution network needed to sustain the hydrogen production and demand across the system. Transmission and small levels of distribution network are required up to 2030 across all scenarios. Starting in and around industrial clusters as expected.
  - Limiting the build of hydrogen transmission networks to link industrial clusters had a limited effect on the amount of hydrogen demand and production technologies deployed. The role of hydrogen infrastructure is being explored in more depth and an addendum to this work will be published.

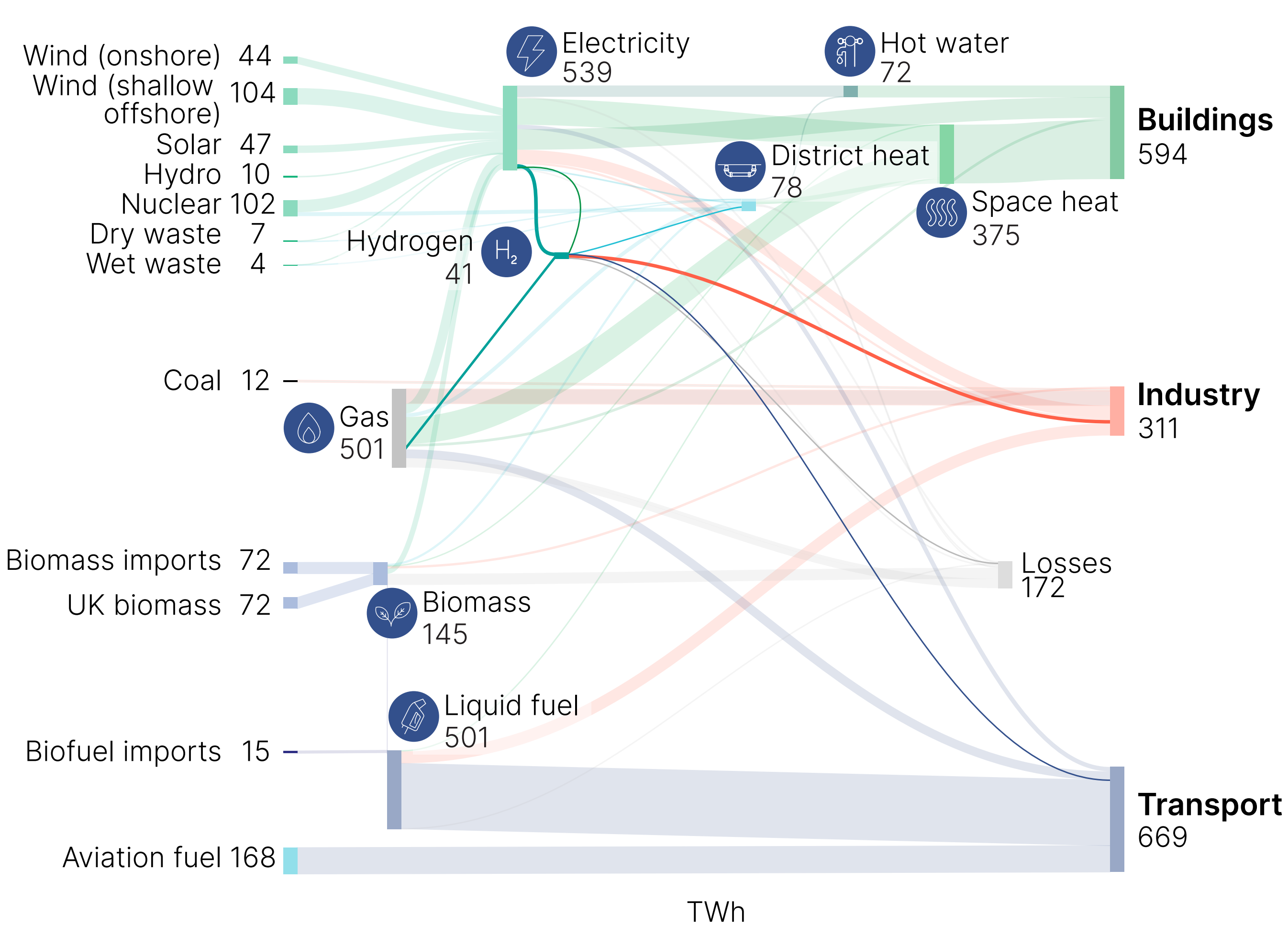


Figure 5. Policy led 2030 Sankey diagram

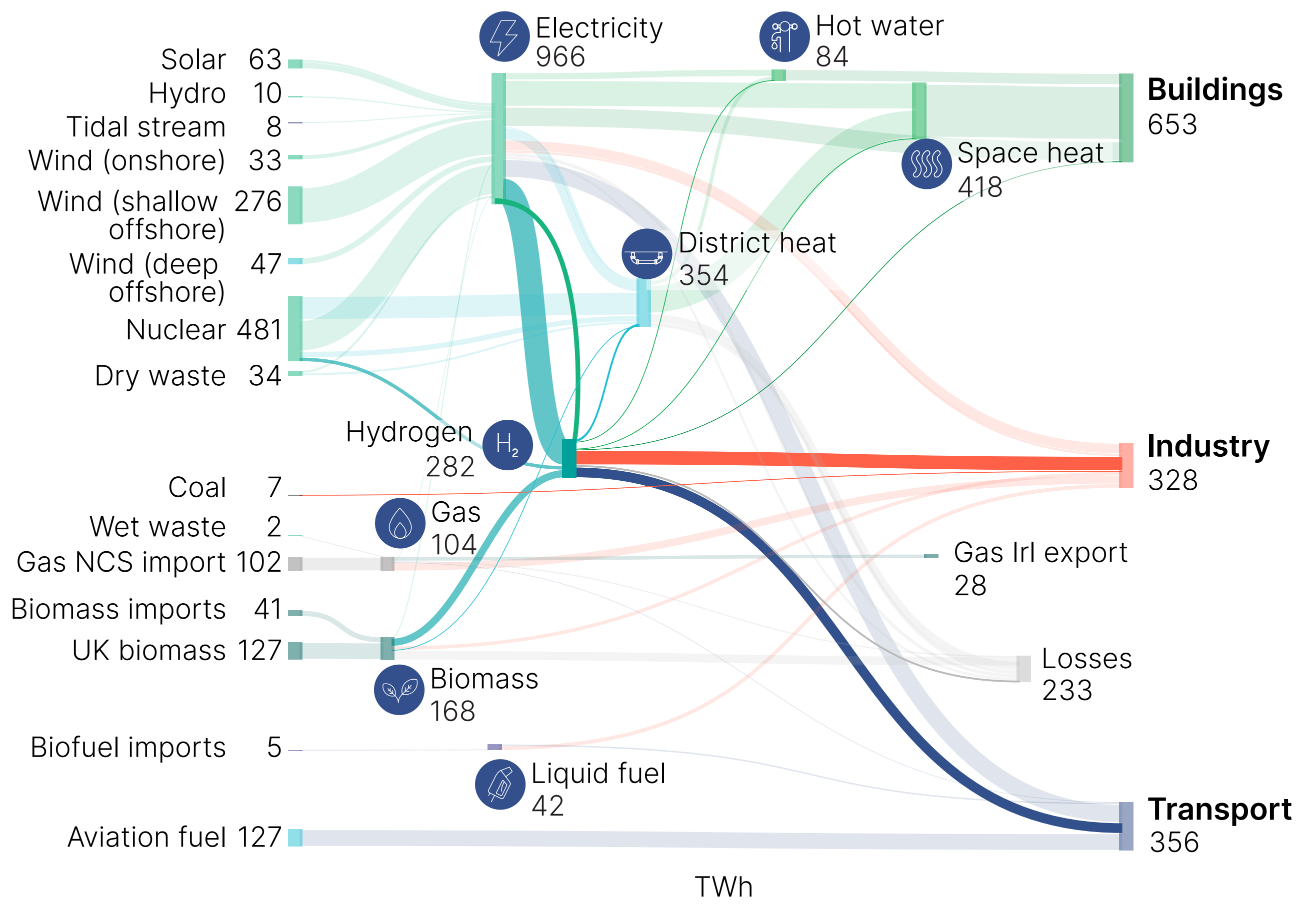


Figure 6. Policy led 2050 Sankey diagram

Policy led 2030 vs 2050 Sankey diagrams

The scale of the shift in estimated demand for hydrogen across the energy system cannot be overstated. Both in terms of the transition from the isolated demands we see today to what would be required by 2030 and the even greater increase needed from 2030 to 2050.

The 2030 and 2050 Sankey diagrams (see Figure 5 and 6) highlight the energy transformations in the policy led scenario. They illustrate the scale up of hydrogen production to 41 TWh by 2030, and up to 282 TWh by 2050, utilising multiple forms of production and with the hydrogen used across the energy system.

The energy system Sankey diagrams portray the energy transformations across the UK energy system from energy inputs to energy consumption.

Units are all in TWh (annual production and consumption).

The “electricity” node includes and represents the efficiency benefits of heat pump deployment.

The modelling uses “resources”, such as natural gas, aviation fuel, coal, biomass, biomass imports. Some of these are constrained, for example, by restricting the estimated availability of biomass imports over time. These sorts of constraints form part of the modelling input assumptions.

- **Hydrogen offers huge potential both in seasonal and diurnal storage (Note that hydrogen storage is not included in the Sankey diagrams). It is a key component in all scenarios with scale up needed to enable the generation commitment by 2030.** Commitments and policies up to 2030 are portrayed across the scenarios including large renewable deployments. Beyond 2030 deployments need to scale up further with approximately 300% increase of offshore wind electricity generation alone estimated to meet net zero. Large quantities of intermittent generation place extra emphasis on balancing the energy system. Being able to satisfy this demand requires hydrogen storage and/or ways of producing hydrogen that can respond in a flexible way. The role of hydrogen in providing this flexibility is being explored in more depth and an addendum to this work will be published.
- Production of hydrogen across the energy system comes in various forms across the scenarios. **Most critical is the production of hydrogen via biomass gasification with CCS (Hydrogen BECCS) resulting in a carbon negative hydrogen fuel.** This helps offset emissions from other hard-to-abate sectors such as industry, aviation, and agriculture. This is echoed by the Climate Change Committee (CCC) and others across several pieces of work [4].
- The level of non-electrolytic hydrogen production in the UK will depend heavily on the amount of carbon dioxide that can be captured, and the availability of biomass, natural gas and waste feedstocks. In each scenario, reformation of natural gas with CCS outweighs the targets, driven by costs and efficiency, and combined with biomass gasification with CCS **goes well beyond the 5 GW minimum capacity specified for 2030.**
- Many of today's natural gas stores and portions of the gas grid remain to 2050 in all scenarios with hydrogen produced on demand.
- **There is significant value to the energy system of being able to increase carbon capture rates from hydrogen production plants up to 99%.** This is highly dependent on the availability of natural gas, natural gas storage and gas networks up to 2050. The UK low carbon hydrogen standard sets a maximum threshold of 20 gCO_2e/MJLHV in the production process for the hydrogen to be considered low carbon [5]. All deployed hydrogen production methods including the energy required to run the plant (e.g., electricity for electrolytic hydrogen production) must meet this standard. Dependent upon the reformation production method the low carbon hydrogen standard could imply a carbon dioxide capture rate between 92% and 94% (based on current data for production methods).
- Generation of hydrogen by nuclear cogeneration plays a role accounting for 2-10% of production across the scenarios. Nuclear cogeneration uses heat generated by the nuclear power station not only to generate electricity but it can also be used for other purposes such as hydrogen generation. If this production method is not available additional hydrogen production from electrolytic methods, and therefore additional generation capacity, will be required.
- An interpretation of the hydrogen business models is implemented in the policy led and hydrogen optimism scenarios. This specifies a minimum 50% (excluding peaks) utilisation factor for electrolytic based hydrogen production in 2030 and 2035. As expected, this drives electrolytic hydrogen production in these scenarios, especially in early years. Whereas in the pessimism and industrial cluster propagation scenarios, capacity is built (due to the capacity build targets) but rarely used prior to 2040 due to operational system impacts and costs. Such costs include the cost to build additional electricity production capacity and the required supporting infrastructure to remain cost competitive against other forms of hydrogen production such as reformation.
- The increased electrolytic hydrogen production that the hydrogen business models incentivise has an impact on the energy system, mainly centred on the electricity generation mix. Figure 7 shows the impact on the electricity generation capacity mix in 2030 in the policy led scenario. One significant consequence is a need for more hydrogen turbines to generate electricity. Additional hydrogen production leads to additional use which in this case occurs through electricity production. **While there is a defined need, incentivising electrolytic hydrogen production could lead to unintended energy system consequences if not aligned with other appropriate measures.**

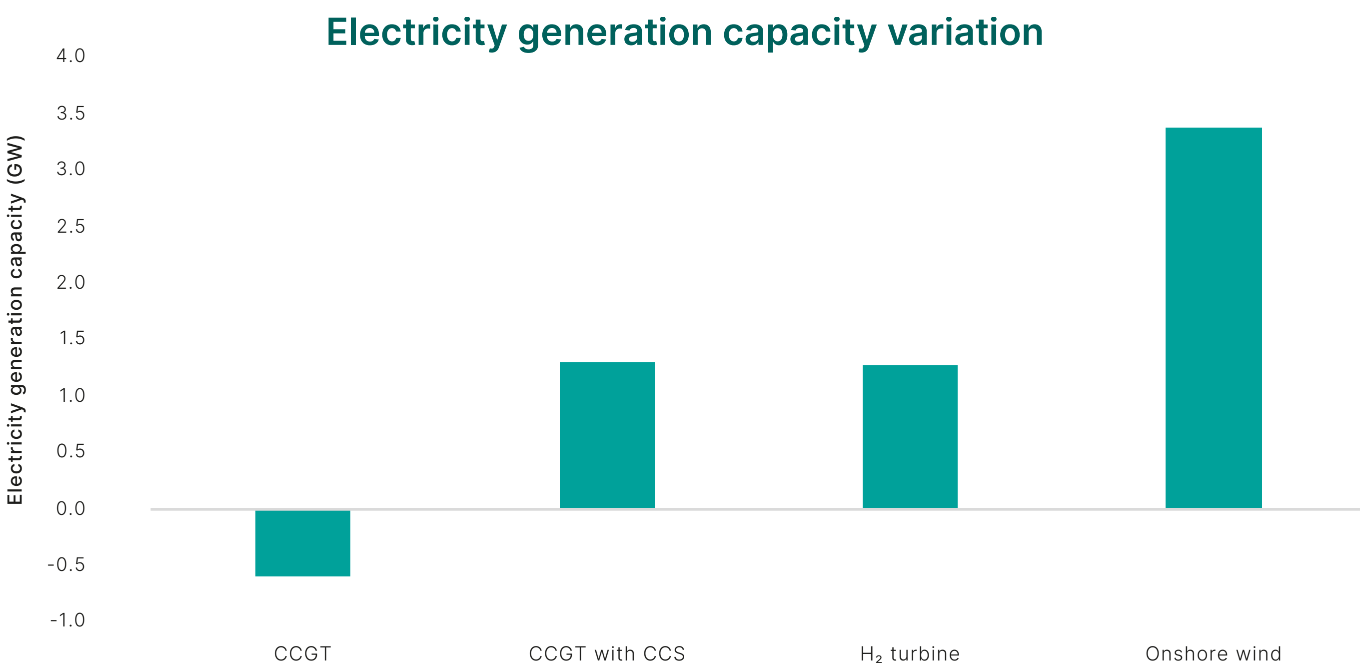


Figure 7. Main variations in electricity generation mix in 2030 when an interpretation of the hydrogen business models is implemented.

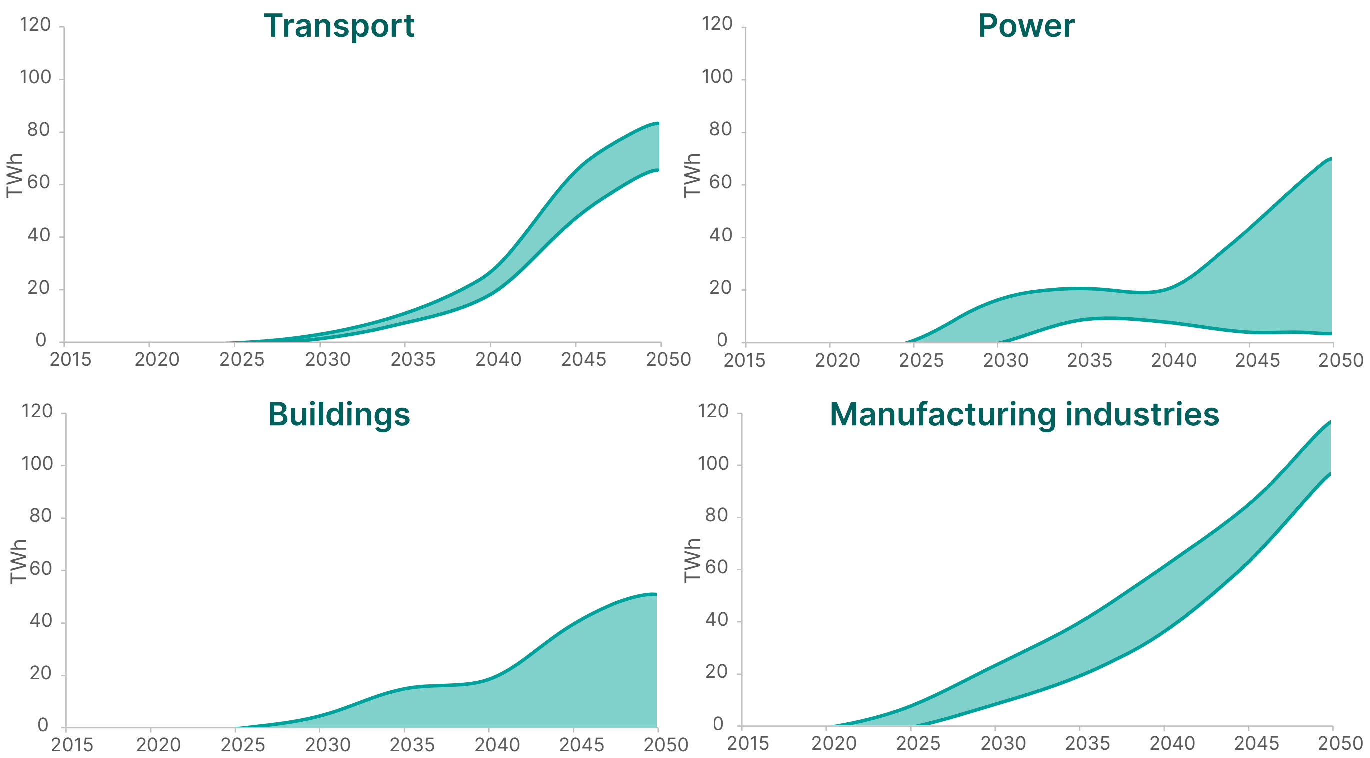


Figure 8. Hydrogen demand across each of the four major sectors for all scenarios.

- Across all scenarios, in the short term (up to 2030), large demands for hydrogen come from the power sector, across industrial manufacturing and early adopters in certain transport sectors (HGV, off-highway and maritime). **In two of the four scenarios the power sector transitions from a baseload provider in the 2030s to play more of a peaking role by 2050, driven by larger deployments of renewables. This presents a decision point for how hydrogen will be supported across the electricity system going forward.**
- Industry and industrial clusters are predicted to be the earliest drivers of hydrogen deployment, production, and usage, in the UK. Although there is niche first deployment and uses elsewhere, industrial deployment of hydrogen is often regarded as the enabler for other sectors, both in the UK and globally. Each of the scenarios see industry as the first mover with heavier transport sectors a close second with demand picking up linearly over time in both sectors (see Figure 8).
- Critical to enable net zero is the removal of carbon dioxide emissions, both in the form of biomass and direct engineered removals from the atmosphere through Direct Air Carbon Capture and Sequestration (DACCS). Biomass transitions from providing a feedstock for electricity generation up to 2030/2035 towards a primary hydrogen generation feedstock through BECCS by 2035-2050.

To identify the innovation opportunities across the hydrogen economy, the technologies needed to produce, handle, and use hydrogen are explored in the following sections in more detail.

Hydrogen production

The UK government has committed to deploy up to 10 GW of low carbon hydrogen production by 2030 with up to 6 GW coming from electrolytic sources, subject to affordability and value for money. The infrastructure and supply chains to support this could contribute to over 12,000 jobs and deliver up to £11bn in private investment [6].

To meet the required hydrogen demand, which could be as much as 40 GW of capacity, by 2050 the UK needs to go well beyond the 10 GW already committed. Several different hydrogen production methods would be expected to meet this demand.

Electrolytic hydrogen production

Global installed electrolyser capacity in 2022 was approximately 690 MW [7]. This is estimated to increase rapidly to reach between 170 and 365 GW by 2030 [7]. To achieve net zero targets globally, electrolyser capacity would need to reach between 4 and 5 TW by 2050 [8].

Hydrogen production: Electrolytic

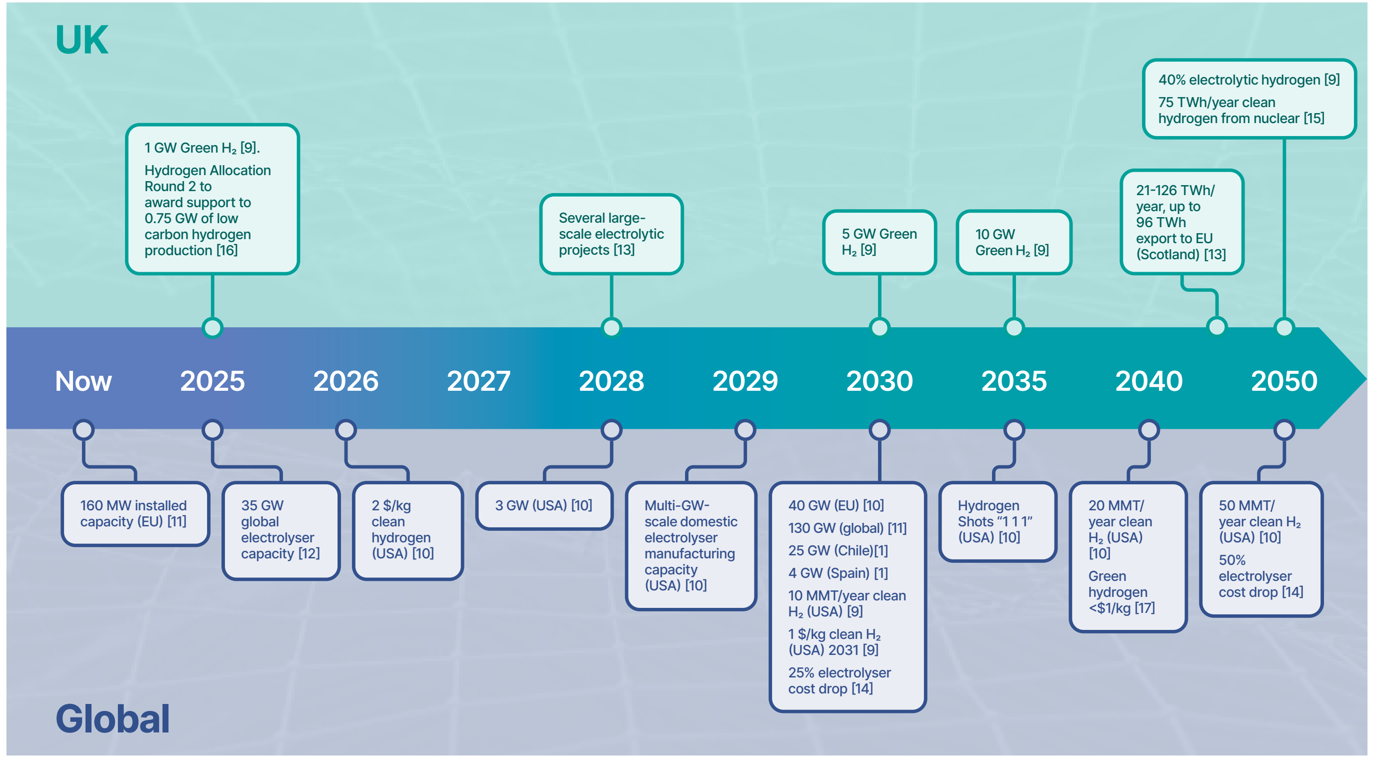


Figure 9. Targets and milestones for electrolytic hydrogen production.

Each scenario implements the UK government commitments apart from the hydrogen pessimism scenario where this commitment is halved to 2.5 GW of electrolytic and 2.5 GW of other low carbon hydrogen production by 2030 to test the material impact of missing the 2030 commitment towards achieving net zero in 2050.

Figure 10 shows the range of electrolytic hydrogen production capacity across the scenarios. In 2030 the minimum is the minimum build specified in the hydrogen pessimism scenario (2.5 GW) and the maximum is the minimum specified in each of the other three scenarios (5 GW). In all scenarios the minimum amount of electrolytic hydrogen production build capacity increases progressively to 2040 then increases significantly. This reinforces the UK government commitment to increase its 2030 ambitions around electrolytic hydrogen production.

Up to 2040 the electrolytic hydrogen production is purely driven by the minimum build requirements. This, in all scenarios, is driven by the cost across the energy system.

Cost includes the capital expenditure of the electrolytic hydrogen production technology and the additional costs across the energy system of utilisation. Beyond 2040 it is driven by the need to produce low carbon hydrogen to meet net zero and interim carbon budget targets. The electricity grid is fully decarbonised by 2035 and any hydrogen production through electrolytic methods would be neutral or negative emission.

Negative emissions, in this context, are those generated using biomass as a fuel source in the production of electricity combined with carbon capture and storage (Bioenergy with Carbon Capture Storage (BECCS)). Carbon is captured from the atmosphere during the growth of the biomass crop, some is sequestered into the soil but the majority into the biomass crop. This carbon is then captured and stored during the production of electricity by BECCS. Resulting in a net sequestration of carbon from the atmosphere.

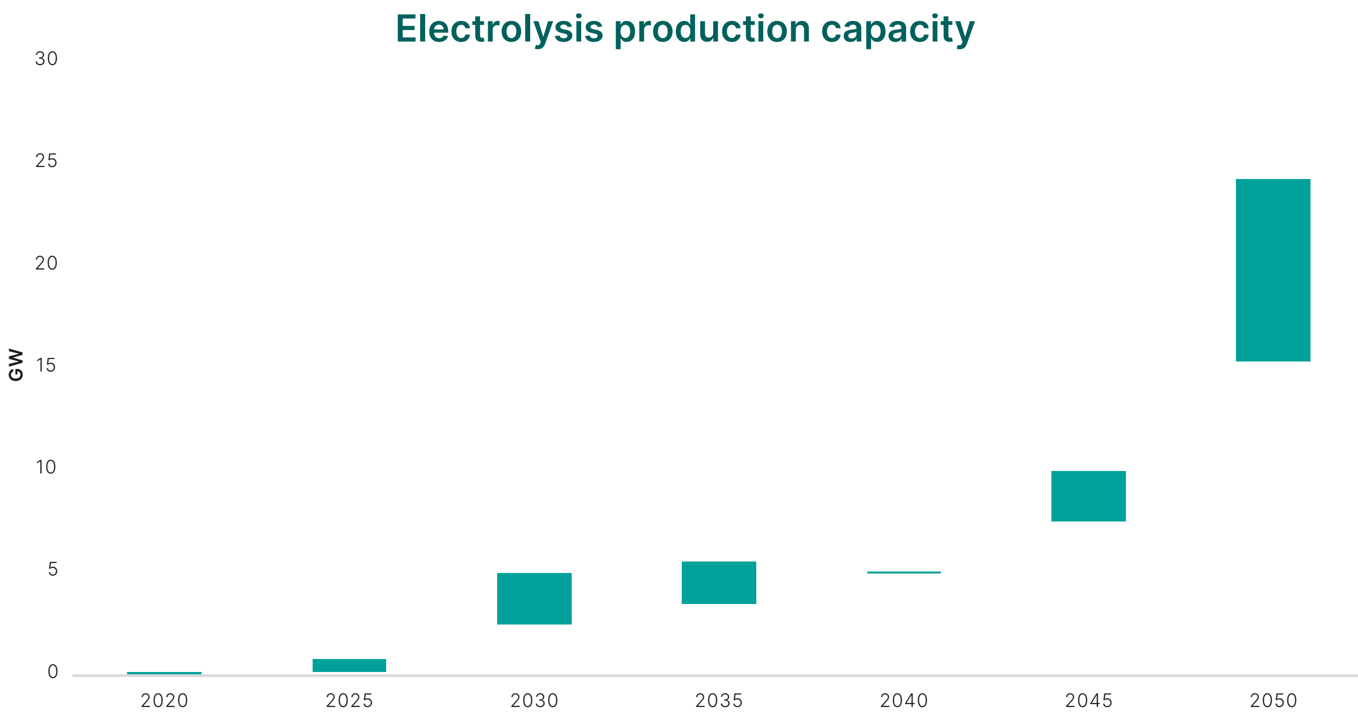


Figure 10. Electrolytic hydrogen production capacity range across the scenarios.

Considering the global market, UK energy security and net zero targets, there are several key technologies which are required for electrolytic hydrogen production. The first is electrolytic hydrogen production, including heat-assisted electrolysers which can exploit waste heat from nuclear power and industrial processes. In addition, balance of plant cost reduction will be key to reducing electrolyser CAPEX which will help to enable higher uptake. Similarly, power electronics will be required to supply the electricity required for electrolytic hydrogen production, especially at scale.

Non-electrolytic hydrogen production

The majority of the 2500 TWh of pure hydrogen produced globally today [18] is made by unabated steam methane reforming, releasing between 690 and 810 Mt CO_2e per year. Current global non-electrolytic low carbon hydrogen production capacity is 20 TWh/yr [19]. This is predicted to increase rapidly to reach between 299 and 400 TWh/yr by 2030 [20].

Hydrogen production: Non-electrolytic

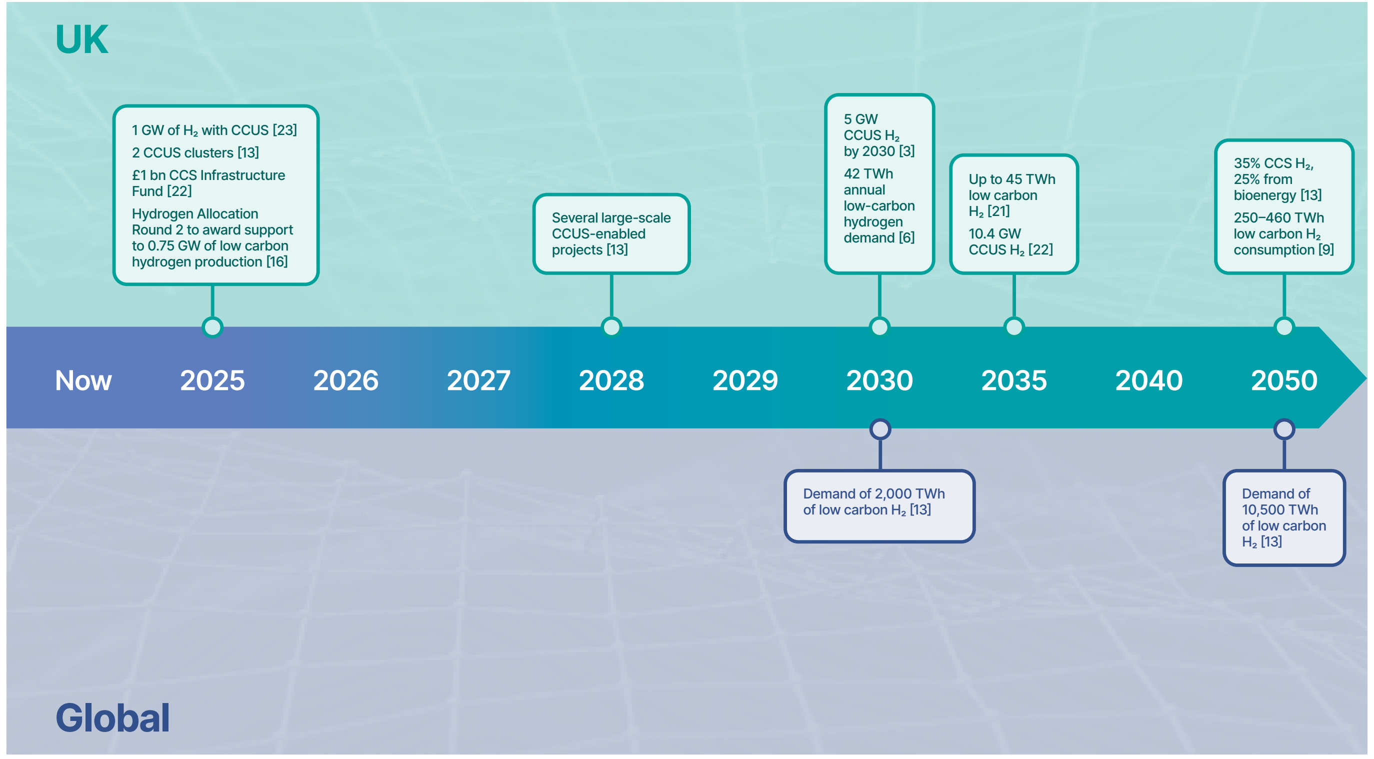


Figure 11. Targets and milestones for non-electrolytic production.

New plant built from today is required to produce hydrogen to a low carbon standard in the UK. Figure 12 and Figure 13 show hydrogen production via biomass gasification and natural gas reformation with CCS progressing from today towards achieving net zero. This also includes existing unabated hydrogen production capacity.

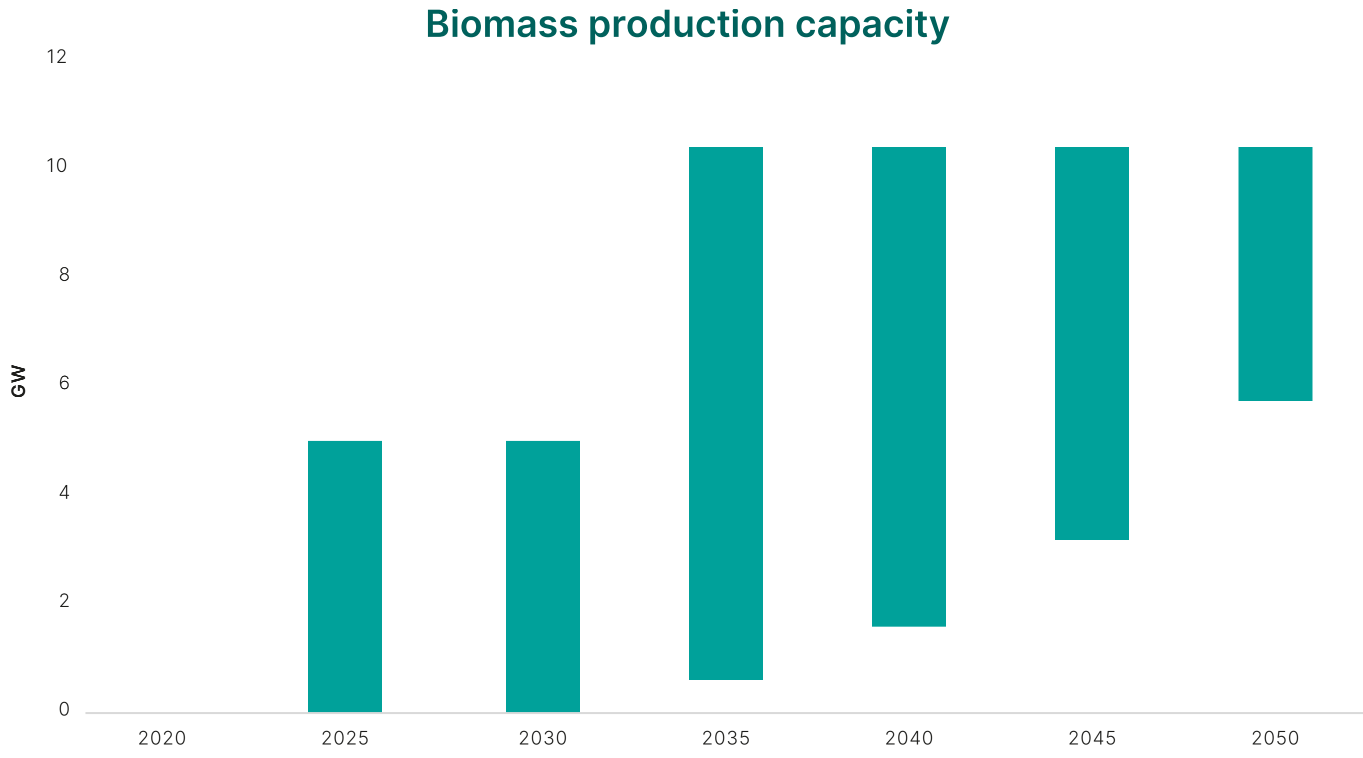


Figure 12. Hydrogen production capacity via biomass gasification with CCS.

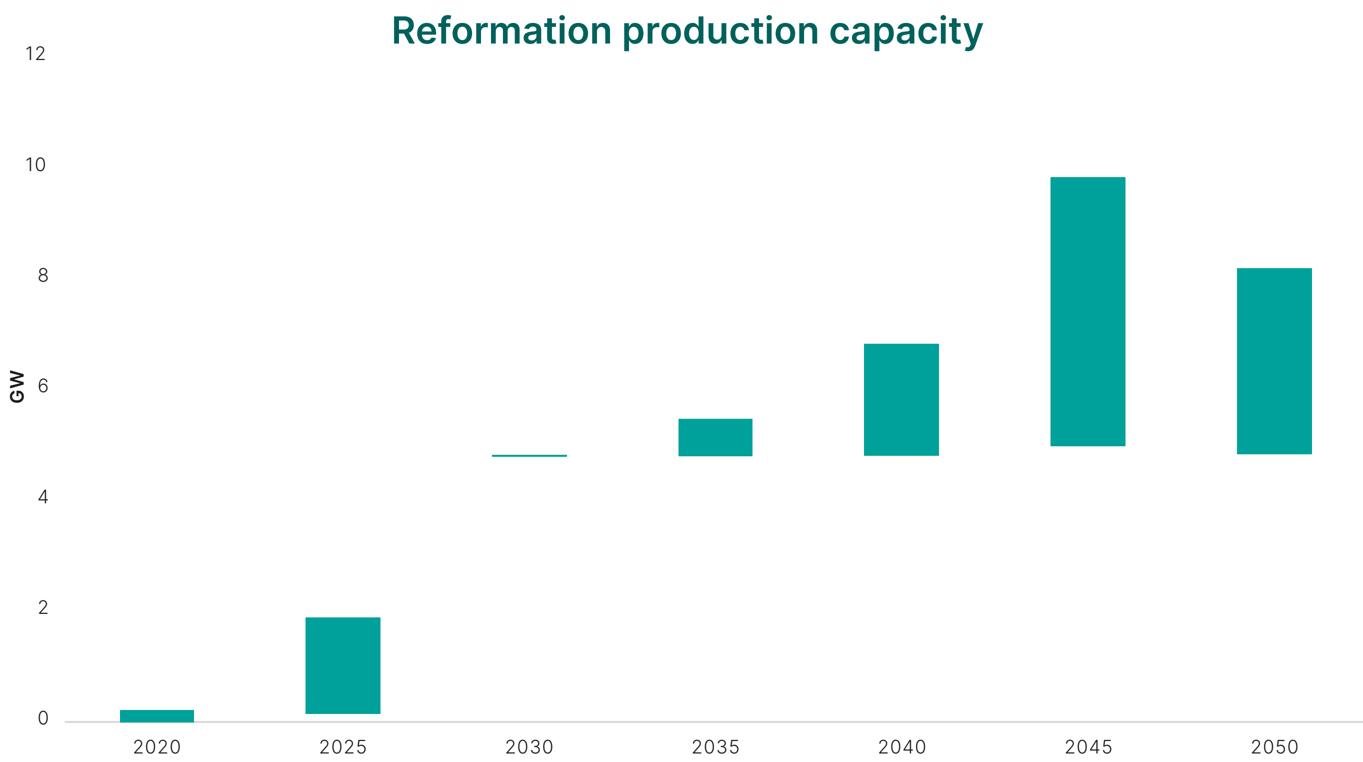


Figure 13. Hydrogen production capacity via natural gas reformation.

Considering the global market, UK energy security and net zero targets, there are several key technologies for non-electrolytic hydrogen production:

- High (>95%) and ultra high (>98.5%) carbon capture technology.
- Biomass gasification.
- Addressing system integration challenges with carbon capture and hydrogen production technologies.
- Thermochemical water splitting hydrogen production which could leverage synergies with the nuclear and solar sectors.
- Breakthrough technologies such as photobiological and photoelectrochemical water splitting which could capture a significant share of the market.

Hydrogen storage and distribution

Hydrogen storage

Hydrogen storage will be a crucial element of the hydrogen economy, with large scale storage supporting the balancing of energy grids, and local hydrogen storage required immediately after production, or just before consumption. Globally, up to 70 TWh of bulk hydrogen storage could be required by 2030 [25], and 1,200 TWh of underground storage alone could be required by 2050 [26].

Hydrogen: Storage

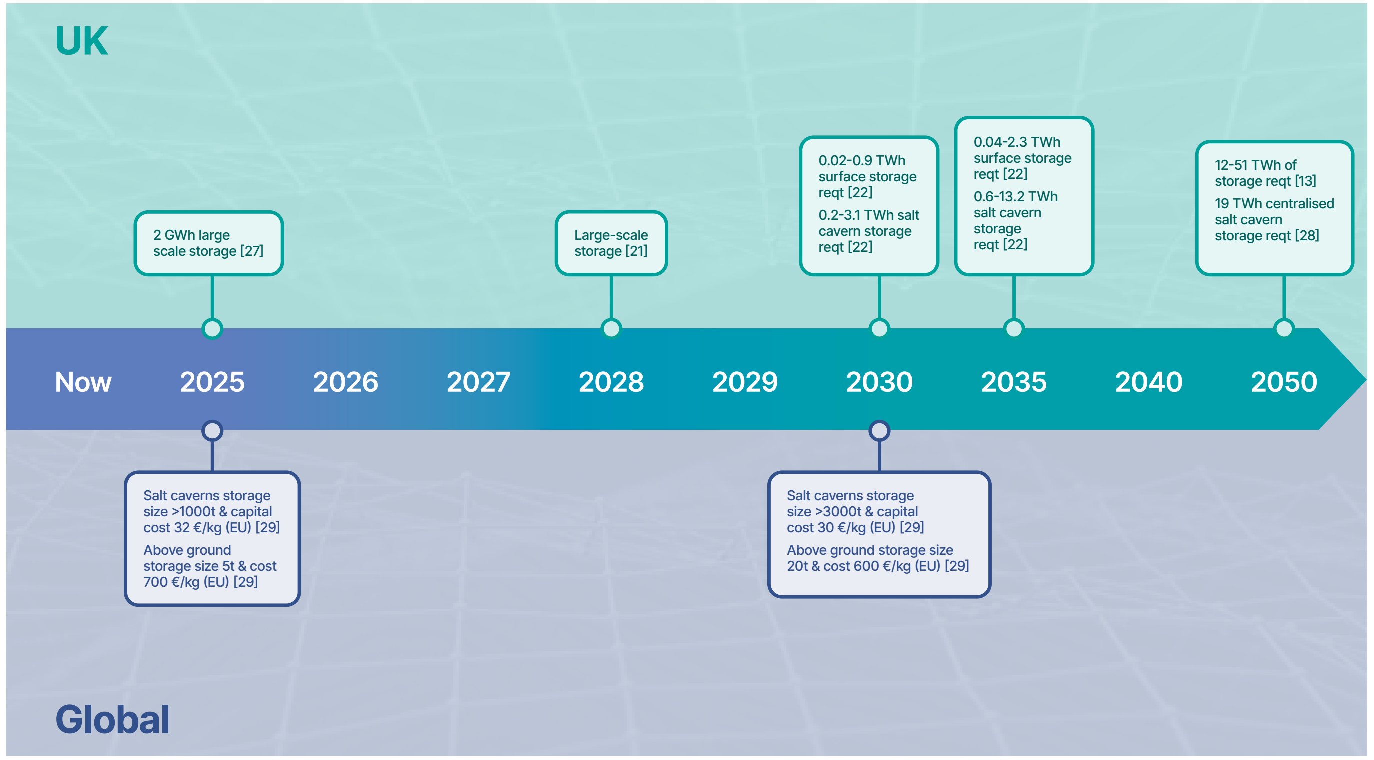


Figure 14. Targets and milestones for hydrogen storage.

In the UK, the potential for large scale and seasonal hydrogen storage, for example, in salt caverns, supports hydrogen grid balancing and energy security, and can be an enabler for the electricity grid to accept a higher proportion of renewable electricity without curtailment. The UK currently has seven salt caverns and depleted gas fields being used as active natural gas storage facilities, providing approximately 1.5bn cubic meters, or 14.5 TWh, of storage capacity [30]. While some of this could be repurposed for hydrogen storage, greater capacity would be requred to store the same amount of energy. National Grid modelling shows that between 12 and 51 TWh of hydrogen storage could be required in 2050 as part of the UK achieving its net zero target [28]. Needs for different levels of hydrogen storage (diurnal vs seasonal, geological vs manufactured cylinders) will be explored in more depth and an addendum to this work will be published.

Key technologies for static hydrogen storage include geological storage, which would help to manage variations in renewable energy generation. Additionally, low cost, static compressed and cryogenic storage will be required at most production and consumption sites and are therefore key to enabling the uptake of hydrogen. Solid state storage offers a promising option, particularly for large-scale long-term storage, as it does not require high pressures or low temperatures.

Hydrogen distribution

While some electrolytic hydrogen may be produced exactly where it is needed, significant amounts of hydrogen will need to be distributed from varying scales of production sites to where it will be consumed. This can be achieved via vehicle (tube trailer), vessel (tanker), or pipeline in several forms such as gaseous, liquid, or in solid storage, or via a carrier such as ammonia or liquid organic hydrogen carrier (LOHC).

Globally, there are about 4,500 km of hydrogen pipeline operating today, including 1,600 km in the USA and a similar amount in Europe. These are generally used to supply large hydrogen users such as petroleum refineries and chemical plants. To stay on track with the IEA global net zero emission scenario, the amount of hydrogen pipelines and transport of low carbon hydrogen would need to increase significantly by 2030 [25].

> **“Globally, there are about 4,500 km of hydrogen pipeline operating today, including 1,600 km in the USA and a similar amount in Europe.**

Hydrogen: Distribution

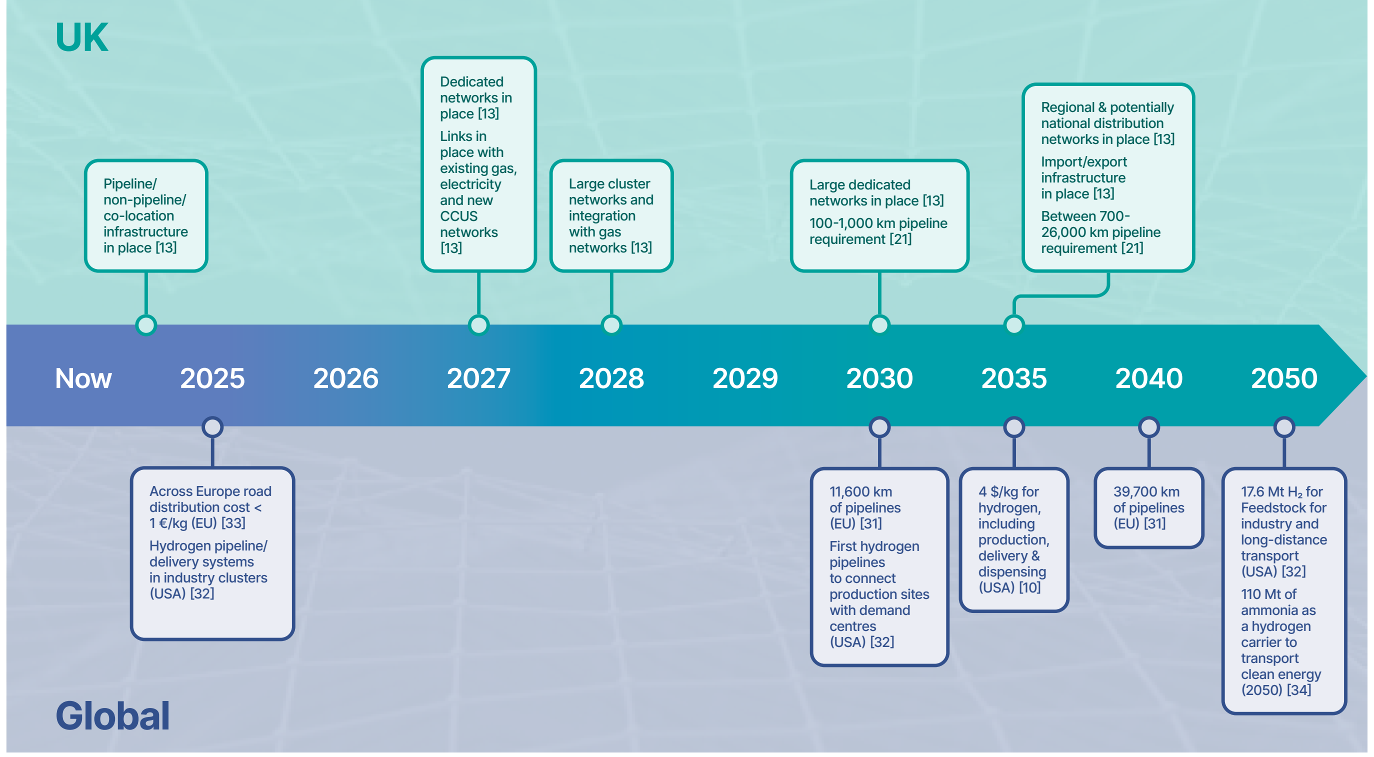


Figure 15. Targets and milestones for hydrogen distribution.

Currently, hydrogen is predominantly transported in gaseous form by tube trailer in the UK. However, government analysis estimates that 700-26,000 km of hydrogen pipeline could be required by 2035 [35] and National Gas' proposed Project Union aims to deliver 2,000 km of hydrogen pipeline connecting production, storage and consumption sites across the UK [36]. The Clean Hydrogen Innovation Programme has listed key distribution technologies such as pipeline infrastructure and tube trailers as high priority technologies in the UK's hydrogen economy based on cost reduction potential and strategic value for the UK's supply chain development [37].

Considering the global market, UK energy security and net zero targets, there could be several key technologies for hydrogen distribution. Hydrogen infrastructure can take the form of road tanker transportation, new pipelines and repurposed pipelines. As the role for hydrogen grows the mix and evolution of hydrogen infrastructure could warrant transitions. If the volumes of hydrogen are high enough and the routes are consistent the economics for national distribution, hydrogen capable pipelines could be required, including technologies which can be used for inspection with minimal disruption to operations. Compressed mobile storage in the form of tube trailers can be used as an alternative to pipeline distribution, particularly for lower volumes.

Hydrogen may be distributed in more energy dense forms including as liquid hydrogen. This will require liquefaction at a large scale as well as cryogenic pumps which could heavily impact the cost of liquid hydrogen. Alternatively, it may be transported as ammonia which will require cracking to release the hydrogen for use.

Irrespective of the distribution form, there is a need for key components including control valves to ensure safety. In addition, efficient distribution and dispensing of hydrogen requires compression, which currently heavily impacts its cost.

Refuelling stations would be needed for all hydrogen-fuelled transport applications. Many of the vehicles using these stations could require high-levels of purification to preserve their operational life. As a result purifiers are an important technology for the hydrogen distibution sector.

The specific needs for different levels of hydrogen distribution (i.e., pipeline and compressed tube trailer) will be explored in more depth and an addendum to this work will be published.

Hydrogen demand

Transport

Transport could become a significant market for hydrogen and hydrogen-derived fuels over the coming decades, focussed on applications and use cases where electrification is unlikely to be viable. Globally, hydrogen demand for transport applications is estimated to reach 630 TWh by 2030 [20]. There is significant uncertainty regarding global hydrogen demand for transport by 2050, though lower estimates still represent a significant market.

In the UK, the modelled scenarios suggest transport related hydrogen demand could reach 68 to 90 TWh by 2050. Figure 16 shows the hydrogen demand breakdown between transport sectors, excluding aviation, for the Policy Led Scenario which models a hydrogen demand from transport of 77 TWh by 2050.

Each transport sector has its own targets, drivers, and associated key technologies.

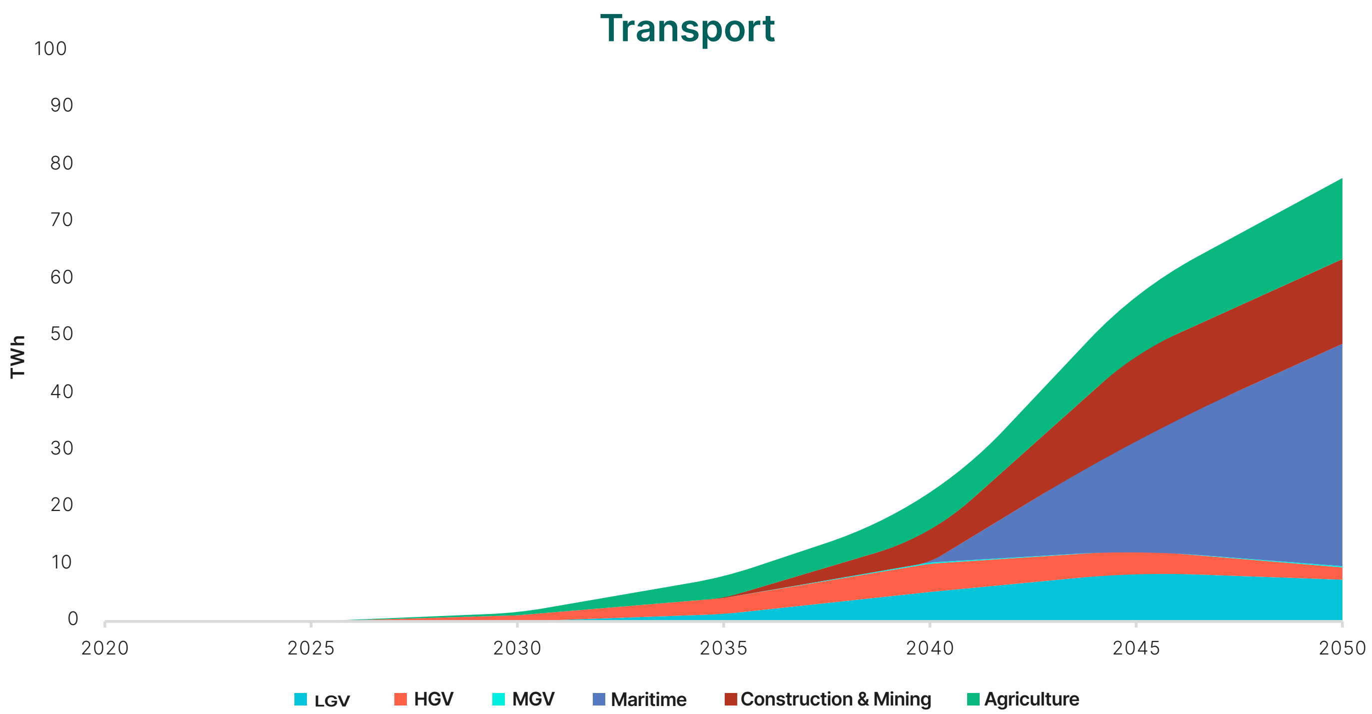


Figure 16. UK transport demand (excluding aviation) for hydrogen in the policy led scenario.

Road, rail, and off-highway vehicles

Hydrogen is estimated to be used for specific applications within the road, rail, and off-highway sectors. For road transport, there are currently about 51,600 fuel cell electric vehicles deployed globally, with the majority being passenger cars. Buses, heavy goods and medium goods vehicles each individually constitute almost 10% of global fuel cell electric vehicle stock at present [38]. However, future uptake is estimated to be predominantly amongst heavier vehicles, while uptake of lighter vehicles is estimated to become mainly battery electric. Limited zero tailpipe emission options currently exist in the medium and heavy duty on-road vehicle sector, but significant developments are underway. Hydrogen may also have an application in the rail sector on routes which are hard to electrify, and 2022 saw the world's first fully hydrogen-fuelled passenger train route in Germany, with 14 two-car vehicles [39].

Off-highway vehicles cover many use cases including agricultural machinery, excavators, backhoe loaders, material handling equipment e.g. forklifts, airport tractors and heavy trucks. These types of vehicles could rely significantly on hydrogen to decarbonise since they are often used in remote areas and require mobile refuelling infrastructure, large amounts of on-board energy, and quick refuelling times.

Globally, there is significant uncertainty around the hydrogen demand from rail and off-highway applications. However, demand for hydrogen in road applications is estimated to reach 133 TWh by 2030 and 2000 TWh in 2050 [20].

Transport: Road, off-highway and rail

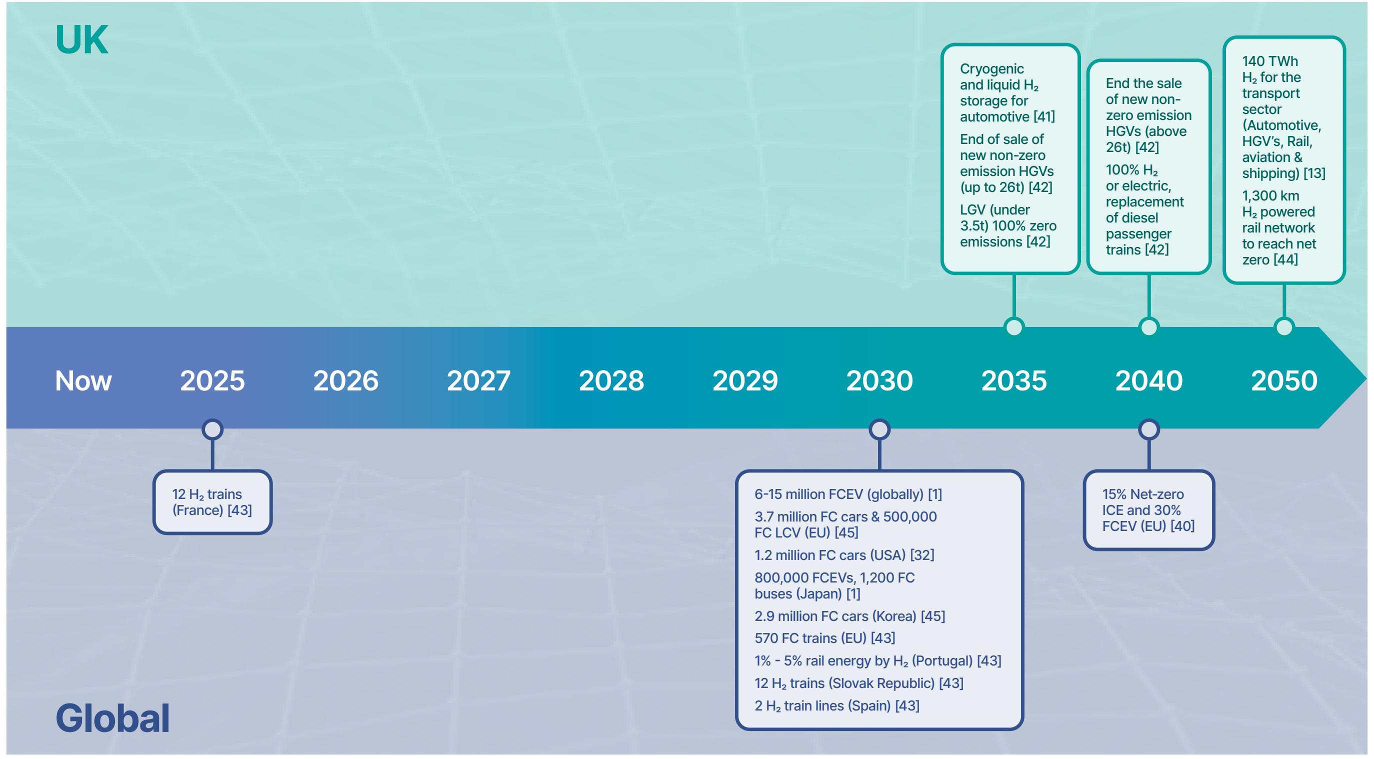


Figure 17. Targets and milestones for road, off-highway and rail.

UK hydrogen use by road transport could account for around 1 TWh in 2030 and 4 - 14 TWh in 2050. Uptake will be highly dependent on vehicle availability, cost to the consumer and infrastructure availability.

All scenarios modelled show little to no propagation of hydrogen through light vehicle categories in the UK, as per the global forecast. For heavier vehicles, in each of the scenarios, a mix of options is deployed between battery, hydrogen and a hybrid of the two. Heavy vehicles require high energy and power density to move and are used in multiple ways, so no one size will fit all. UK hydrogen use by road transport could account for around 1 TWh in 2030 and 4 - 14 TWh in 2050. Uptake will be highly dependent on vehicle availability, cost to the consumer and infrastructure availability.

Hydrogen or hydrogen derivatives are the dominant off-highway vehicle deployed across the scenarios with around 29 TWh of hydrogen consumed. Most off-highway vehicles often operate at high load (power intensive) for long periods requiring large amounts of on-board energy and quick refuelling times. This makes pure battery electric vehicles impractical for most applications. Off-highway vehicle manufacturers have been innovating and showcasing demonstration vehicle capabilities for several years. In some instances, zero emission vehicle options have already propagated through to commercialisation e.g. airport handling vehicles.

Many off-highway vehicles, especially in the construction and mining sectors, are unique in that they often have second and third "lives" beyond the original purchaser or user in the UK or elsewhere. This presents potential issues for existing supply chains providing vehicle support and infrastructure elsewhere globally (at the second or third life location).

Key technologies for the road, rail, and off-highway sectors include fuel cells and the necessary power electronics for the fuel cell system. While fuel cells are well suited to many on-road applications, hydrogen internal combustion engines offer a compelling proposition in high-power applications for construction, mining, and agricultural platforms. Both fuel cell and internal combustion applications will use onboard compressed hydrogen storage tanks.

Aviation

Hydrogen could play a role in the decarbonisation of aviation through two routes. Firstly, as a direct fuel either in fuel cells or jet engines, for smaller single-aisle aircraft. Secondly, using hydrogen as a feedstock for sustainable aviation fuel (SAF) which could be the main future aviation fuel, especially for long haul flights. Globally, there is significant uncertainty regarding future hydrogen demand for aviation (including hydrogen as a feedstock for SAF) in both 2030 and 2050. This is driven largely by uncertainty around the adoption of hydrogen-powered aircraft, and the uptake of synthetic SAF made from non-biogenic origins. However, even low estimates suggest there could be significant hydrogen demand in aviation by 2050.

Transport: Aviation

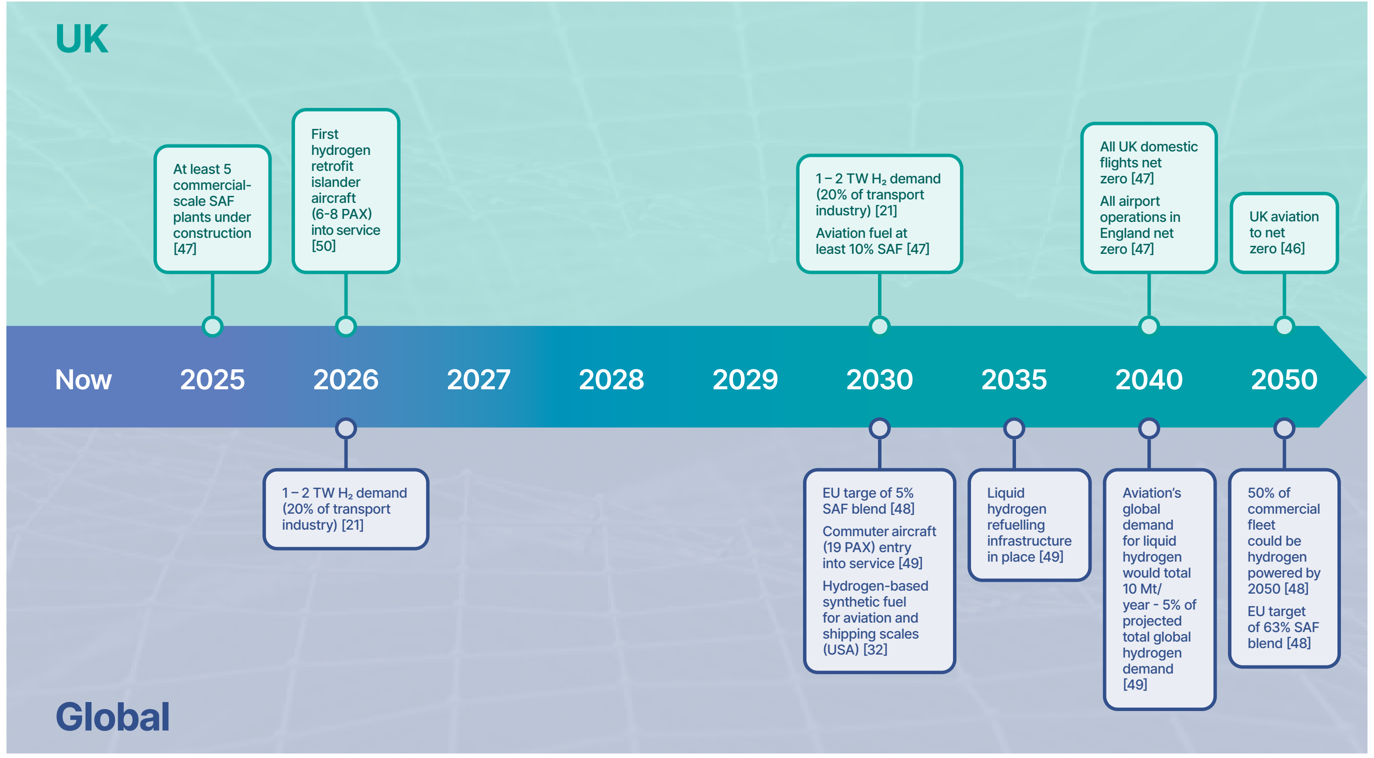


Figure 18. Targets and milestones for aviation.

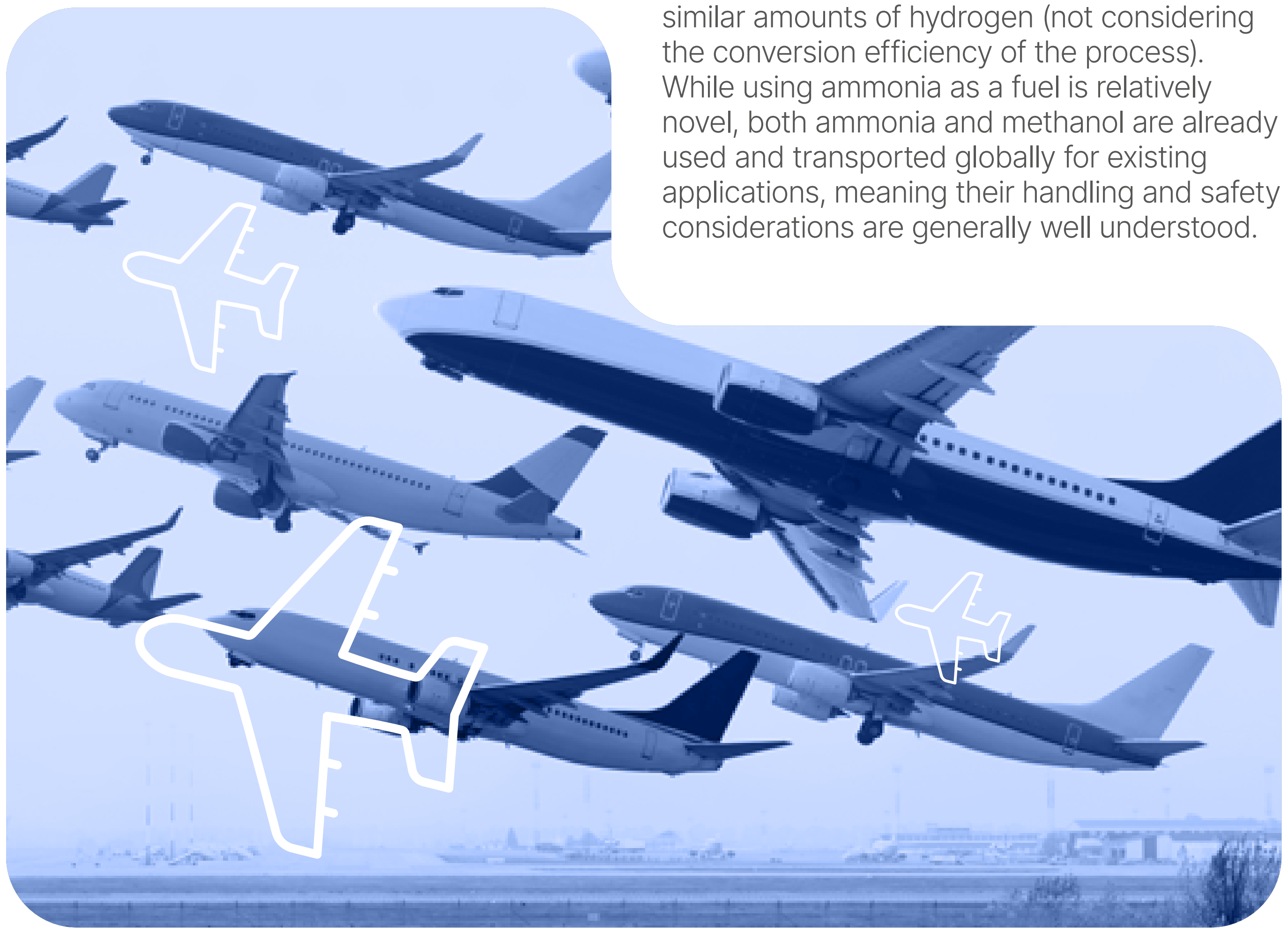
Demand for hydrogen in aviation will not be solely influenced by a need to meet net zero. Regional and narrowbody segments offer the most viable first mover for direct hydrogen uses with potential demand up to 20 TWh by 2050. When combined with other low emission fuels such as synthetic SAF, hydrogen demand for use in aviation could be much higher by 2050 [51]. The role of hydrogen in aviation and in providing sustainable aviation fuel is being explored in more depth and an addendum to this work will be published.

Demand for hydrogen in SAF is estimated to be low in 2030, although there are specific targets for SAF in 2035. As an example, only 3 TWh of hydrogen could be required to meet demand for eSAF at EU airports by 2030 to meet the ReFuelEU Aviation directive [52], [53]. However, this is estimated to rise significantly by 2050, largely driven by increased SAF mandates and advancements in Power-to-Liquid (PtL) technology. While significant, the global demand for hydrogen in SAF by 2050 is subject to uncertainty. This is largely due to the unpredictable penetration of hydrogen aircraft and the proportion of SAF demand.

For hydrogen use in aviation, several key technologies exist. For aircraft, fuel cells are well suited to power regional aircraft, and hydrogen gas turbines for regional, narrow-body and midsize aircraft. Most hydrogen-powered aircraft will need to store hydrogen onboard in liquid form due to its superior energy density and therefore lightweight cryogenic storage tanks will be required. In addition, cryogenic pumps will be critical components of aircraft propulsion systems.

To manage the extreme temperatures, compact, integrated and efficient heat exchangers are needed to remove heat from propulsion systems, while minimising aerodynamic drag. For fuel cell aircraft which require power electronics, any cooling systems can be used to increase their durability and performance.

Beyond zero emission flight, technologies to manufacture SAF will be important from an energy security perspective by reducing reliance on imports. Unlike methanol and ammonia, SAF is only intended for use in aviation and will not have other use cases in the chemical and manufacturing industries. However, much of the supply chain for production of SAF (e.g. carbon dioxide capture, Fischer-Tropsch synthesis) could be required in the production of other synthetic chemicals including synthetic diesel, methanol and ammonia.



Maritime

The maritime sector could drive significant demand for hydrogen as it decarbonises. Global use of hydrogen for maritime could reach 1533 TWh by 2050, with demand largely dominated by feedstock requirements for ammonia and e-methanol [54]. It is estimated that 10% could also be used directly as liquid hydrogen through fuel cells and internal combustion engines [54]. Methanol powered vessels such as the Laura Maersk [55] are already operating commercially. Demand for methanol could scale in the short to medium term (2023-2030) with over 100 methanol-fuelled vessels estimated to be delivered by 2028 [56].

There remains significant uncertainty whether one fuel will dominate the maritime sector. However, the front runners for large ships – ammonia and methanol – would both demand similar amounts of hydrogen (not considering the conversion efficiency of the process). While using ammonia as a fuel is relatively novel, both ammonia and methanol are already used and transported globally for existing applications, meaning their handling and safety considerations are generally well understood.

Transport: Maritime

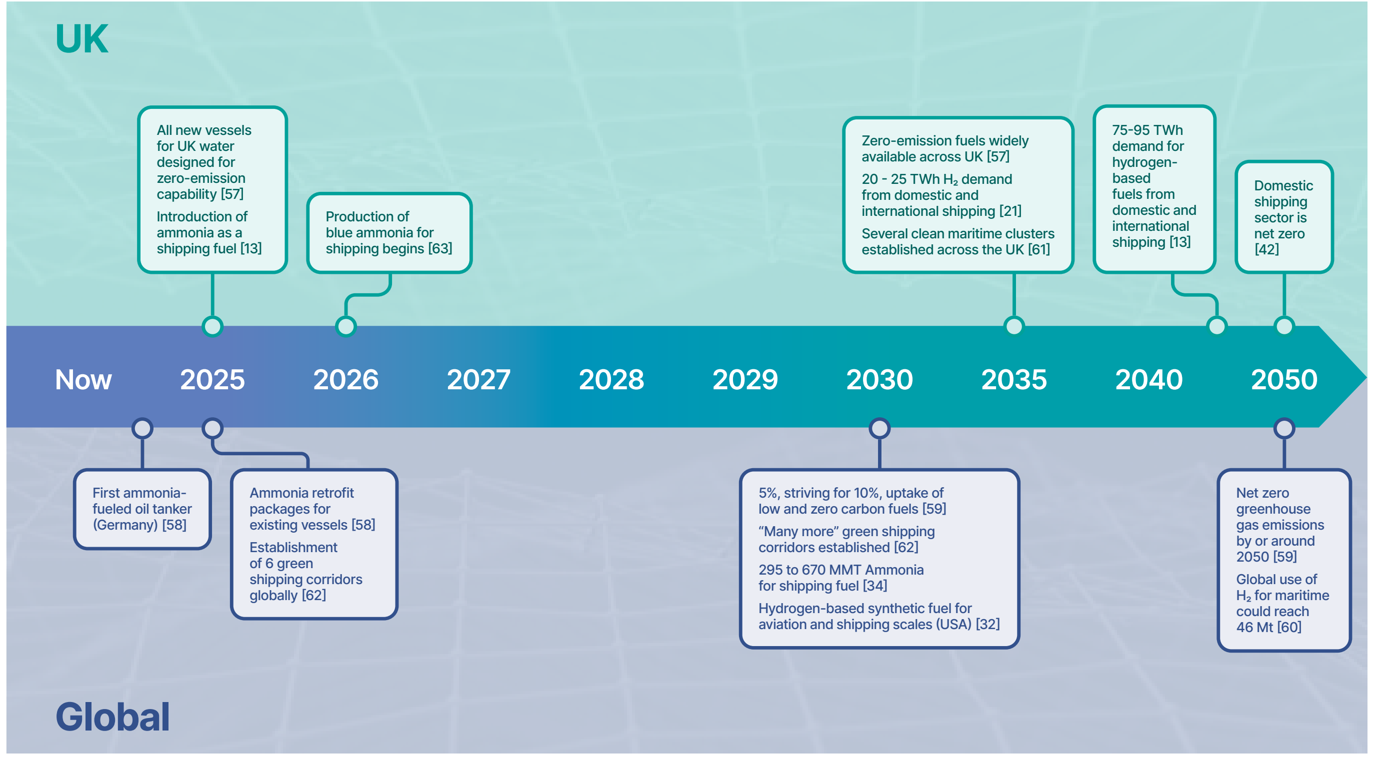


Figure 19. Targets and milestones for maritime.

Demand for hydrogen and hydrogen-derived fuels for UK maritime will depend largely on UK trade growth and the share of bunkering for international vessels at UK ports. The UK only supplies around 50% of the energy demand of its share of international shipping currently, as much of the bunkering for international shipping happens at large international hubs such as Rotterdam. However, this may change with lower energy density net zero fuels requiring more bunkering events. The annual demand for hydrogen in the UK's maritime sector could reach 39 TWh by 2050.

Considering the global market, UK energy security and net zero targets, key technologies for the maritime sector include fuel cells for small and mid-size vessels in the domestic fleet, as well as internal combustion engines powered by ammonia, methanol and hydrogen for larger vessels which have higher load and power requirements. Once onboard, storage and risk mitigation measures for these alternative fuels will be important for maintaining safety for crew and passengers.

Additionally, technologies which can enable fast and safe dispensing of ammonia and methanol for international shipping will be required to ensure vessel turnaround times are comparable with current operations. Vessels could experience more bunkering events due to the reduced energy density of alternative fuels. Ensuring efficient turnaround times is therefore crucial for a functioning global maritime market.

The technology requirements for synthesising ammonia and methanol are considered in **'Chemical production'**.

Industry

Hydrogen is already used as a feedstock in the chemical industry and in refineries, as part of a mix of gases in steel production, and for process heat generation in certain industries. In this report, 'manufacturing industries' also includes the production of chemicals such as ammonia and methanol for use in the manufacture of fertilisers, plastics, and other products.

Demand for hydrogen in manufacturing industries is estimated to grow steadily as those currently using fossil fuels for heat and/or chemical processes look to decarbonise. The global demand for hydrogen in manufacturing industries is estimated to escalate, by reaching 3,500 TWh by 2030 [20]. By 2050, this figure is estimated to further increase to around 5,000 TWh [26].

"The global demand for hydrogen in manufacturing industries is estimated to escalate, by reaching 3,500 TWh by 2030.

Hydrogen demand for manufacturing industries in the UK could reach 105 TWh by 2050 (Figure 8). Figure 20 shows the range of hydrogen demand breakdown by heat type requirement for manufacturing industries sectors across the scenarios.

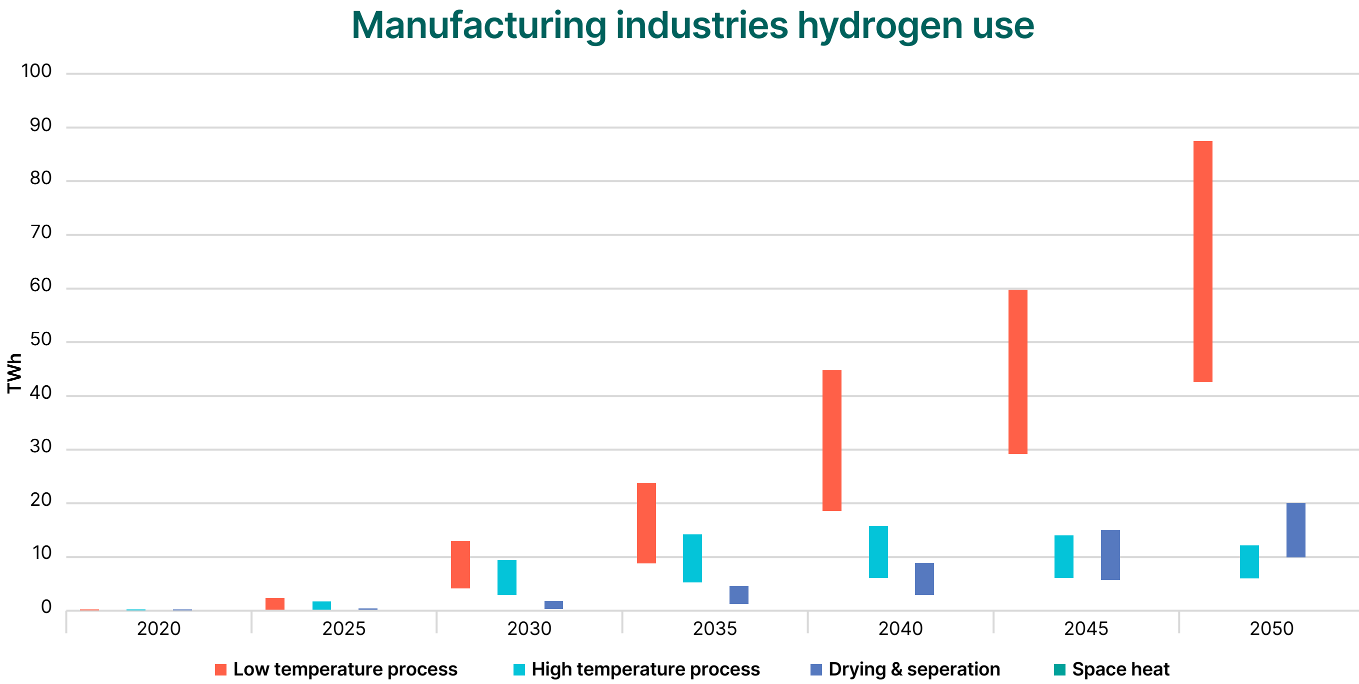


Figure 20. Demand for hydrogen in manufacturing industries. Low temperature process heat is a process heat up to ≈250°C. High temperature process heat is a process heat above ≈250°C. Drying and separation is defined as process which uses heat to dry and/or separate products or chemicals, its commonly used in pharmaceutical, chemical, food and paper industries. For example, to dry out paper by passing it through heated rollers.

Foundation industries and refining

Hydrogen could be used for decarbonisation of high temperature industrial processes including both refining and foundation industries.

In the context of a national energy system, 'foundation industries' refers to those sectors that are energy-intensive and form the basis of the industrial structure. These industries such as steel, cement, and glass, as well as certain food production such as sugar, could increasingly look to hydrogen where processes are challenging to electrify. Globally, foundation industries are estimated to use 600 TWh of hydrogen per annum by 2030 [20], [25].

Currently, one of the primary applications of hydrogen is in refining. However, as the demand for oil products diminishes, the need for hydrogen in this sector is estimated to decline. Despite this, for the foreseeable future some hydrogen could still be needed for refining and it is important that this is low carbon hydrogen. The current global demand for hydrogen for refining is around 1,400 TWh (in 2022) and this is estimated to reduce to 1165 TWh in 2030 and only 333 TWh in 2050 [20], [26].

Globally, hydrogen demand from the combination of foundation industries and refining could reach around 1800 TWh by 2030 [20]. Significant uncertainty exists, particularly within foundation industries where the degree to which processes can be electrified is not yet clear.

Industry: Foundation industries and refining

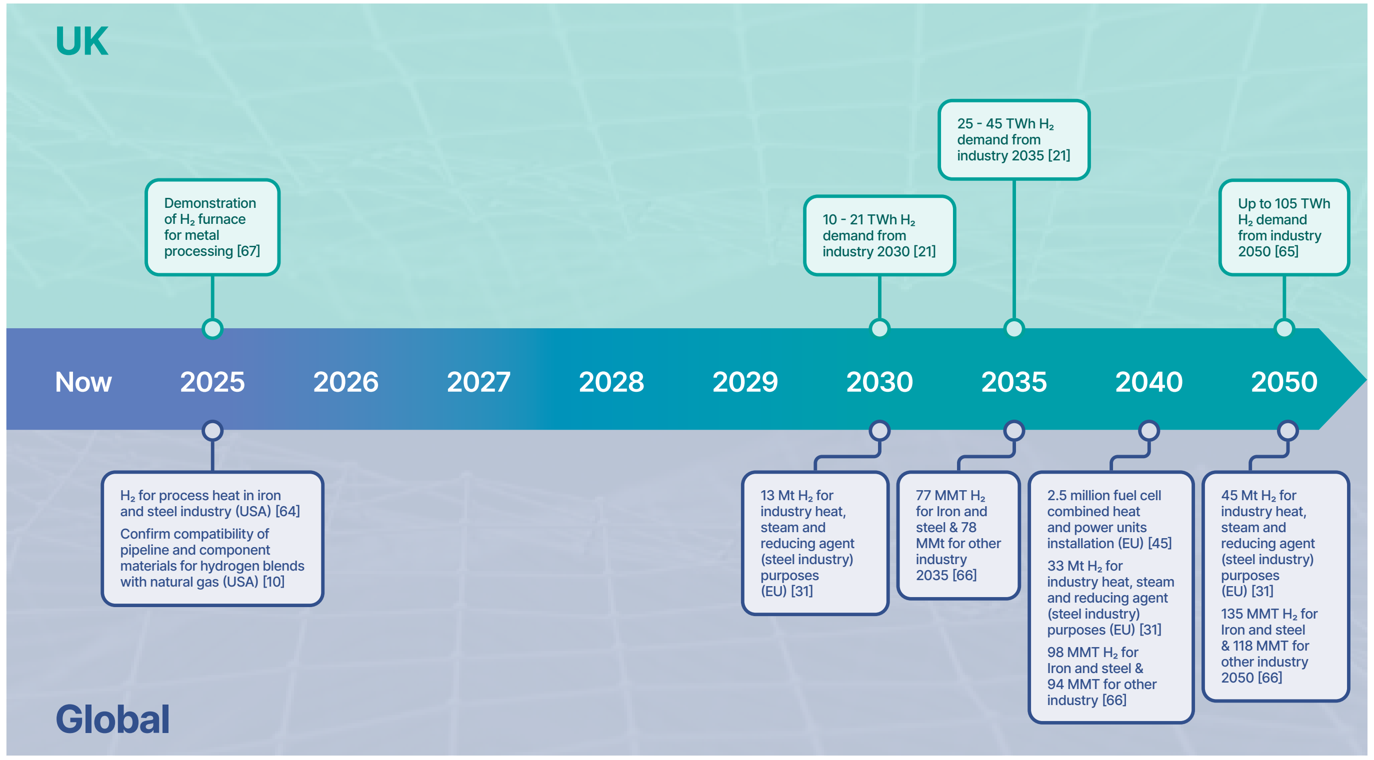


Figure 21. Targets and milestones for industry and refining.

Considering the global market, UK energy security and net zero targets, key technologies for hydrogen in foundation industries and refining include hydrogen-powered furnaces and dryers, enabled by new refractory materials which are compatible with hydrogen. However, as hydrogen combustion in air emits NO_x, furnaces can be equipped with measuring probes and abatement systems, allowing for effective control of these pollutants. Hydrogen direct reduction of iron (hydrogen DRI) has the potential to decarbonise part of the steel manufacturing process. However, there is significant uncertainty as to whether the UK will retain its iron reduction capability.

> **Global hydrogen demand for chemical production could reach 1800 TWh in 2030, rising to 2000 TWh by 2050.**

Chemical Production

Global hydrogen demand for chemical production could reach 1,800 TWh in 2030, rising to 2000 TWh by 2050 [26].

Industry: Chemical conversion

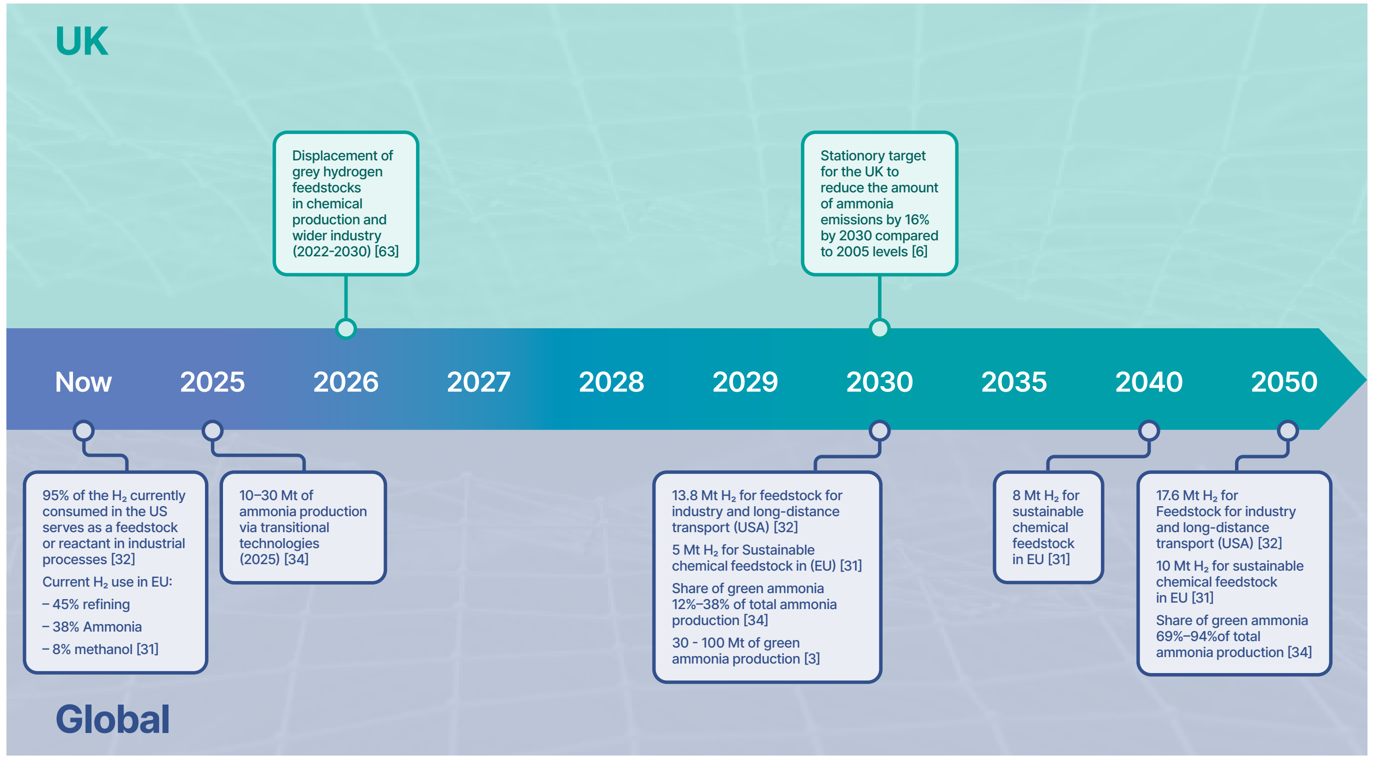


Figure 22. Targets and milestones for chemical conversion.

Potential use cases for hydrogen as a chemical feedstock in the UK are evolving. Currently, the production of ammonia is relatively minimal due to the increasing costs of energy compared to other countries and several production sites have been closed recently. However, the landscape may shift with a rise in demand from various sectors by 2050. Similarly, the role of the UK in the production of e-methanol is still unclear.

If the UK were to pursue the production of ammonia, methanol, and other synthetic fuels for transport applications, this capability could be leveraged for chemical production. As such, the potential for hydrogen as a chemical feedstock in the UK will be influenced by a variety of economic, technological, and policy factors.

Considering the global market, UK energy security and net zero targets, technologies to enable ammonia and methanol synthesis from hydrogen are key. As well as fertilisers, cleaning products, de-icers, and plastics, these chemicals are expected to be key in decarbonising international shipping due to their superior energy density compared to other fuels. Synthesising these fuels in the UK will reduce reliance on imports.

Power generation

Hydrogen can be converted to electrical power either for remote or backup power generation, or at a larger scale as part of a grid balancing system. Solid Oxide Fuel Cells (SOFCs) are currently used as power sources for data centres, mainly generating power through the conversion of carbon-based fuels such as natural gas and biogas into hydrogen, which then undergoes a chemical reaction to generate power. These fuel cells can also be powered directly with hydrogen though this is not the norm due to the cost and availability of hydrogen [68]. Proton-exchange membrane (PEM) fuel cells powered by hydrogen are also being explored as backup power options at these facilities, replacing diesel generators.

Globally, hydrogen demand for power generation applications is estimated to reach 730 TWh/yr by 2030 and around 2,500 TWh/yr by 2050 [69].

In the UK, hydrogen demand for power generation is expected to play a role. Although the exact type of role is uncertain with all scenarios indicating hydrogen could play a base load role in power up to 2030 with an estimated hydrogen demand up to 10 TWh. Beyond 2030 hydrogen transitions are to play more of a 'peaking' role, providing extra standby capacity utilised when electricity demand cannot be met with renewables and other baseload means. This is estimated to be between 4-72 TWh by 2050 (see Figure 24).

Considering the global market, UK energy security and net zero targets, key technologies for hydrogen electricity generation for the grid include hydrogen gas turbines. At a local scale, stationary fuel cells and internal combustion engines can provide electricity in off-grid locations and in backup power solutions in place of diesel generators. Underpinning all hydrogen power generation technologies are power electronics, needed to manage the electricity generated by each technology.

Industry: Power generation

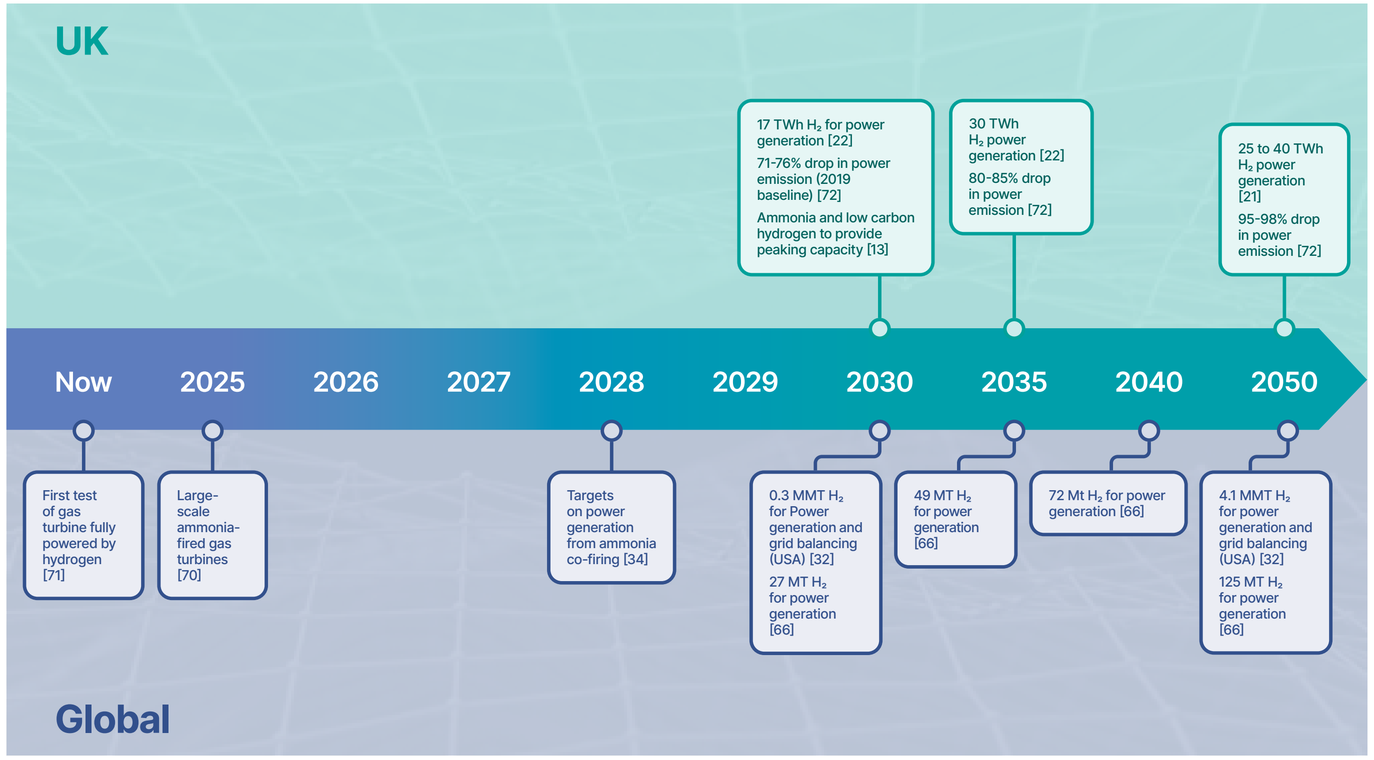


Figure 23. Targets and milestones for power generation.

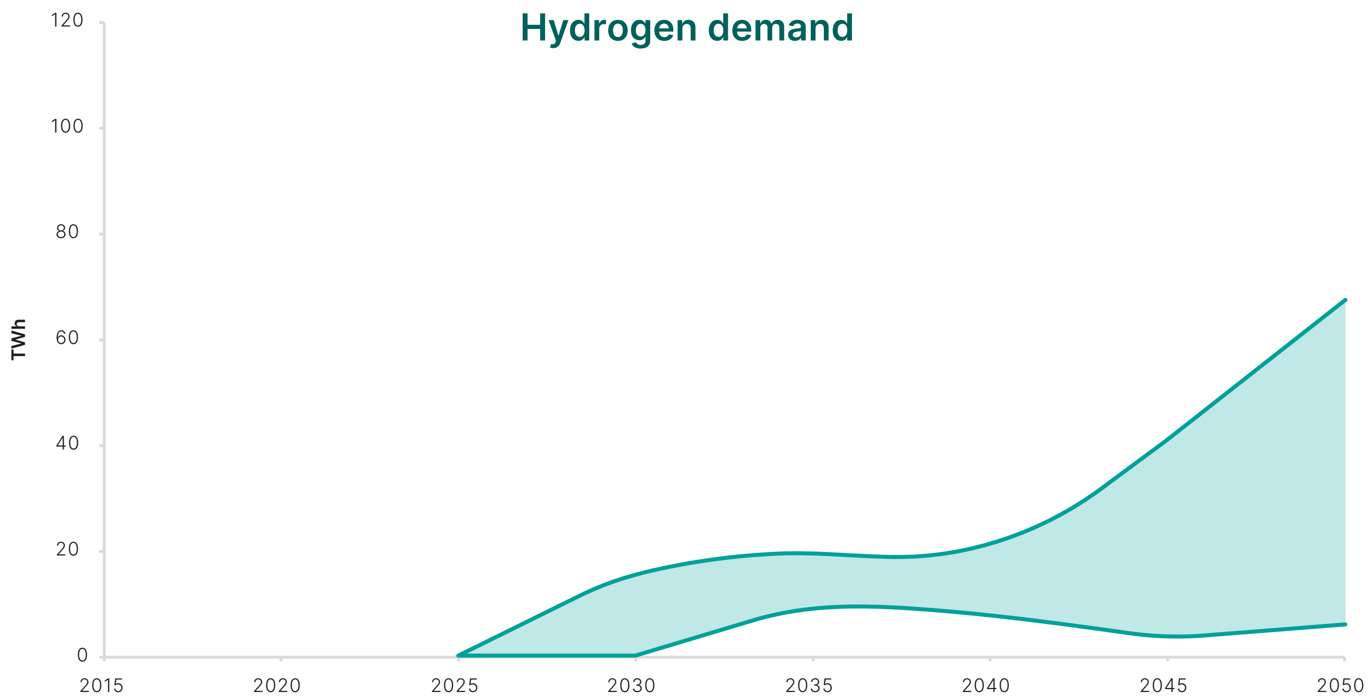


Figure 24. UK hydrogen demand scenarios for power generation across all scenarios

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