Table 2.2: Overview of selected hydrogen production methods

Production method	Definition	Carbon Intensity estimates[18]	Levelised Costs[19]	Role to 2030 / 2050	Next steps
Steam methane reformation without carbon capture	Natural gas with methane reformation, mostly for use in petro-chemical sector	83.6 $gCO_2e/MJ\ H_2$ (LHV)	SMR (300MW) 2020: £64/MWh 2050: £130/MWh	Small amounts of existing supply have helped prove end use case in tests / trials.	Decarbonise existing use in industry
Steam methane reformation (SMR) or autothermal reformation (ATR) with carbon capture	Natural gas with methane reformation, but with CO2 emissions captured and stored or reused	ATR with CCS: 16.0 $gCO_2e/MJ\ H_2$ (LHV) SMR with CCS: 21.4 $gCO_2e/MJ\ H_2$ (LHV)	ATR (300MW): 2020: £62/MWh 2050: £65/MWh SMR (300MW): 2020: £59/MWh 2050: £67/MWh	Large scale projects expected from mid-2020s, bulk supply to kick start UK hydrogen economy	Carbon capture and storage infrastructure needs to be in place
Grid electrolysis	Using electricity from the grid to electrolyse water, splitting it into hydrogen and oxygen.	78.4 $gCO_2e/MJ\ H_2$ (note this is a blended figure using grid averages to calculate)	PEM (10MW): 2020: £197/MWh 2050: £155/MWh	To be determined based on further policy development	Further engagement and analysis required, e.g. via the consultation on the UK Low Carbon Hydrogen Standard
Renewable electrolysis	Using clean electricity to electrolyse water, splitting it into hydrogen and oxygen	0.1 $gCO_2e/MJ\ H_2$ (LHV)	PEM (10MW) (with dedicated offshore wind): 2025: £112/MWh 2050: £71/MWh	Small projects expected to be ready to build in early 2020s	Scale up technology, reduce costs over time

Production method	Definition	Carbon Intensity estimates[18]	Levelised Costs[19]	Role to 2030 / 2050	Next steps
Low temperature nuclear electrolysis	Low temperature electrolysis from existing nuclear facilities	Not modelled but expected low GHG emissions.	Not modelled by BEIS	Can apply existing technologies to current plants in the 2020s.	Further developments expected in 2020s.
High temperature nuclear electrolysis	High temperature nuclear power to electrolyse water	High temperature electrolysis: 4.8 $gCO_2e/MJ\ H_2$ (LHV)	Not modelled by BEIS	Could develop hydrogen from advanced nuclear for 2030s	Further innovation and developments expected in 2020s.
Bioenergy with carbon capture and storage (BECCS)	Biomass gasification with carbon capture and storage	-168.7 $gCO_2e/MJ\ H_2$ (LHV)	BECCS (473MW) 2030: £95/MWh (excl. carbon) £41/MWh (incl. carbon) 2050: £89/MWh (excl. carbon) -£28/MWh (incl. carbon)	Could begin production in 2030s	Further innovation and developments expected in 2020s. Developing position further in forthcoming Biomass Strategy
Thermochemical water splitting	Direct splitting of water using very high temperature heat from advanced modular nuclear facilities	Not modelled but expected low GHG emissions.	Not modelled by BEIS	Could develop hydrogen from advanced nuclear for mid-late 2030s	Further innovation work to develop to commercial technology
Methane Pyrolysis	Heat splits natural gas into hydrogen and solid carbon	Not modelled, but expected low GHG emissions	Not modelled by BEIS	Nascent technology still to be proven at scale	R&D / Innovation

Working with industry, the UK's ambition is for 5GW of low carbon hydrogen production capacity by 2030. This ambition is based on our understanding of the pipeline of projects that could come forward during the 2020s, and takes into account the challenges, constraints and costs involved in delivering this. As we work towards this ambition, we would hope to see the first gigawatt of low carbon hydrogen production capacity in place by 2025. This is a fast-evolving market, however, and we will need to ensure we continue to develop our understanding as trends develop and policy decisions influence investments. We believe that working towards 5GW of production capacity by 2030 is a stretching but deliverable ambition, building on the UK's strong track record of delivering significant cost reductions and large-scale deployment of offshore wind and solar power, and will put us on a credible trajectory aligning with a pathway to net zero.[20] Achieving this ambition is a key outcome for our strategy and is expected to bring forward over £4 billion of private investment in the period up to 2030.

To meet this ambition, the UK has committed to a 'twin track' approach to hydrogen production, supporting both electrolytic and CCUS-enabled hydrogen, ensuring we support a variety of different production methods to deliver the level of hydrogen needed to meet net zero. This approach sets the UK apart, giving us a competitive advantage and building on our strengths to ensure we can be confident in delivering our 2030 ambition and beyond. As outlined in Chapter 1, the UK's skills, capabilities, assets, and infrastructure mean that we have the potential to excel in both electrolytic and CCUS-enabled low carbon hydrogen production. Supporting these and other potential production routes will enable us to develop low carbon hydrogen rapidly at scale while future-proofing our net zero ambitions.[21]

This twin-track approach has already underpinned successful innovation through our Low Carbon Hydrogen Supply Competition, which set out to support development and cost reduction of a wide range of world-leading technologies. This has supported projects including methane reformers with higher carbon capture rates, scaling up of modules and support for the automated manufacture of electrolysers, and work to evidence the feasibility of electrolysis from low carbon nuclear.

As set out in the analytical annex published alongside this strategy, the proportion of hydrogen which will be supplied by particular technologies depends on a range of assumptions, which can only be tested through the market's reaction to the policies set out in this strategy and real, at-scale deployment of hydrogen across our complex energy system. Our Hydrogen Production Cost 2021 report suggests that, under central fuel price assumptions, CCUS-enabled methane reformation is currently the lowest cost low carbon hydrogen production technology. Given the potential production capacity of CCUS-enabled hydrogen plants, we would expect this route to be able to deliver a greater scale of hydrogen production as we look to establish a UK hydrogen economy during the 2020s. However, as referenced in Table 2.2 above, costs of electrolytic hydrogen are expected to decrease considerably over time, and in some cases could become cost-competitive with CCUS-enabled methane reformation as early as 2025. Given the range of uncertainties and variable assumptions in this area, and the rapid growth we need to meet our carbon budgets, we consider support for multiple production routes the most appropriate approach, rather than reliance on a single technology pathway.

How will we develop and scale up low carbon hydrogen production over the 2020s?

Our commitment to supporting multiple production routes will, we believe, bring forward the broad range of projects needed to ensure a rapid and cost-effective build out of the hydrogen economy. Greater competition will spur innovation, cost reductions and investment across the value chain. Deploying CCUS-enabled hydrogen capacity will achieve cost-effective near-term low carbon hydrogen production at scale, drive investment across the value chain (including transmission, distribution and storage), and pull a range of hydrogen technologies through to commercialisation. Alongside this, supporting the scale up of electrolytic hydrogen production can drive down costs to establish a cost-optimal and credible technology mix for our pathway to net zero. Our focus will be on promoting domestic production and supply chains, although we would expect to be an active participant in international markets as they develop, maximising export opportunities and utilising import opportunities as appropriate.

The first movers in the early 2020s are likely to be relatively small (up to 20MW) electrolytic hydrogen projects that can be deployed at pace, with production and end use closely linked, for example, at a transport depot or industrial site. By the mid-2020s we could start seeing larger (100MW) electrolytic hydrogen projects and the first CCUS-enabled hydrogen production facilities based in industrial clusters. At this stage producers could be catering for a growing range of customers across transport, industry and power generation as well as potential to supply hydrogen heat trials and blend low carbon hydrogen into the gas grid. By the end of the decade we could have multiple large CCUS-enabled (500MW+) production facilities across the UK, with extensive cluster networks and integration into the wider energy system. Achieving our 2030 ambition is expected to provide up to 42TWh of low carbon hydrogen for use across the economy.

Case study: ITM Power – electrolytic hydrogen production

Based in Sheffield, ITM Power are a world-leading manufacturer of PEM (proton exchange membrane) electrolysers, a technology for hydrogen production from water. The company's new Gigafactory is the world's largest electrolyser factory with a 1GW per annum capacity to produce renewable hydrogen for transport, heat and chemicals. In May 2020, ITM Power announced plans to establish a separate subsidiary – ITM Motive – to build, own and operate eight publicly accessible H_2 refuelling stations.

Several ITM projects are supported by government. The company's Gigastack project – led alongside Ørsted, Phillips 66 Limited and Element Energy – won funding from BEIS' Low Carbon Hydrogen Supply Competition. Gigastack is developing electrolyser technology to produce renewable hydrogen at industrial scale.

The exact production mix by 2030 will be influenced by a range of factors, such as carbon pricing and the policies being consulted on in parallel to this strategy. Alongside this, investor confidence and market forces will dictate the type of projects that will come forward during the 2020s. In the longer term, electrolytic hydrogen offers greater carbon reduction potential and cost reductions, making it cost-competitive with CCUS-enabled

hydrogen over time.[22] Using the 2020s to 'learn by doing', supported by research and innovation, will provide lead-in time needed to enable commercial production of electrolytic hydrogen at larger scale from the 2030s onwards, ensuring it can plug into a wider hydrogen value chain commercialised through large scale CCUS-enabled production.

Investors, developers and companies across the length and breadth of the UK are ready to build if the right policy environment is in place. We are aware of a potential pipeline of over 15GW of projects, from large scale CCUS-enabled production plants in our industrial heartlands, to wind or solar powered electrolysers in every corner of the UK. This includes plans for over 1GW of electrolytic hydrogen projects, ranging from concept stage to fully developed proposals, which are aiming to deploy in the early 2020s. Other production methods being proposed by industry include using biomethane or the electricity or heat from a nuclear reactor as energy inputs to hydrogen production.

Case study: Acorn Project – CCUS-enabled hydrogen production

Led by Pale Blue Dot Energy, the Acorn CCS and Hydrogen Project in St Fergus, Scotland (image left), aims to deliver an energy- and cost-effective process for low carbon hydrogen production for use in a range of applications including industrial fuel switching and decarbonising heating. The project, supported through BEIS' Low Carbon Hydrogen Supply Competition, conducted engineering studies to evaluate and develop the advanced reformation process, including assessment of Johnson Matthey's low carbon hydrogen technology and an alternative reformer technology.

From the 2030s onwards, we may see a wider range of production technologies coming to the market including more hydrogen from nuclear, using low carbon heat and power from small modular and advanced modular reactors, as well as bio-hydrogen with CCUS that can deliver negative emissions. A dynamic market will include multiple sources and end uses for hydrogen.

To meet our CB6 and net zero targets, there is likely to be a substantial ramp up in demand beyond 2030. Our analysis suggests that hydrogen demand could increase significantly in the early 2030s, suggesting 7-20GW of production capacity may be needed by 2035.[23] Demand could continue to increase rapidly over the 2030s and 2040s, requiring a corresponding increase in hydrogen production capacity to ensure there is sufficient supply to meet this.

In achieving our 2030 5GW ambition and delivering production levels needed for CB6 and net zero, we will have to work with industry and other stakeholders to better understand and overcome the barriers to growing a new energy vector for the UK. These barriers reflect the strategic challenges outlined in Chapter 1.5 and include:

- High production cost relative to high-carbon fuel alternatives.
- High technological and commercial risks for maintaining operation of first-of-a-kind projects and investment in next-of-a-kind deployment.
- Demand uncertainty due to current limited use of low carbon hydrogen in the UK.
- Lack of market structure, small number of end users potentially leading to the abuse of market power.
- Distribution and storage barriers, reflecting the current lack of sufficient carbon capture and storage and hydrogen transmission infrastructure.
- Policy and regulatory uncertainty, including the lack of established standards to define low carbon hydrogen (including non-emission standards), and related to the limited understanding of the regulatory impacts of hydrogen at a system-wide level.

Detailed description of these barriers can be found in the analytical annex (chapter 2).

What are we doing to deliver new low carbon production?

This strategy marks a turning point for low carbon hydrogen production in the UK. It is part of a comprehensive package of measures, set out by government alongside the strategy and beyond, that can help deliver our 2030 5GW production ambition and ensure that we are ready for the step-change needed in low carbon hydrogen production in the 2030s to help meet our CB6 commitments and put us on a pathway to net zero:

- **Research and innovation:** The UK is already at the forefront of research and innovation across the hydrogen value chain, reducing technological, environmental, social and economic barriers to production and end use. **We also recently launched our £60 million Low Carbon Hydrogen Supply 2 Competition, which will develop novel hydrogen supply solutions for a growing hydrogen economy.**

- **CCUS infrastructure:** In November 2020 we confirmed allocation of £1 billion for the Carbon Capture and Storage (CCS) Infrastructure Fund, to help overcome carbon capture, distribution and storage barriers and enable the establishment of a new CCUS sector. **In May this year, we set out the details of the Carbon Capture, Usage and Storage (CCUS) Cluster Sequencing Process, which will look to identify at least two CCUS clusters for deployment in the mid-2020s.** Projects within the clusters will have the opportunity to be considered to receive any necessary support including access to the CCS Infrastructure Fund, and business models for transport and storage, power, industrial carbon capture and low carbon hydrogen.

- **Hydrogen Business Model:** In the Prime Minister's *Ten Point Plan*, we confirmed our intention to develop business models to help bring through investment in new low carbon hydrogen projects and help build UK capability to meet net zero. Since then, we have worked to develop a Hydrogen Business Model intended to provide long-term revenue support to hydrogen producers to overcome the cost challenge of producing low carbon hydrogen compared to cheaper high-carbon alternatives. We consider our preferred business model would provide an investable commercial framework for producers while also meeting government's objectives for developing the low-carbon hydrogen market and ensuring value for money. **Further detail on our proposals is set out in the** Hydrogen Business Model Consultation **published alongside this strategy. We intend to provide a response to this consultation alongside indicative Heads of Terms in Q1 2022.**

- **Net Zero Hydrogen Fund (NZHF):** As set out in the Prime Minister's *Ten Point Plan*, **the NZHF will provide up to £240 million of government co-investment to support new low carbon hydrogen production out to 2025, kickstarting efforts to deliver our 2030 5GW ambition.** The aim of the Fund is to support commercial deployment of new low carbon hydrogen production projects during the 2020s, helping to address barriers related to commercial risk and high production costs of hydrogen compared to fossil fuel alternatives. We are consulting on the design and delivery of the NZHF alongside the publication of this strategy, and **we intend to launch the NZHF in early 2022.**

- **Low Carbon Hydrogen Standard:** If we are to achieve our CB6 and net zero commitments, we must ensure that the hydrogen production we are supporting is sufficiently low carbon, while not stifling innovation and growth. To help address barriers related to policy and regulatory uncertainty, we have identified and assessed a series of options for a UK low carbon emissions standard that could underpin the deployment of low carbon hydrogen. Alongside this Strategy we have published a report, prepared for government by E4Tech and Ludwig-Bölkow-Systemtechnik (LBST), which explores a range of factors including maximum acceptable levels of greenhouse gas (GHG) emissions associated with low carbon hydrogen production and the methodology for calculating these GHG emissions. **Alongside this strategy, we have also published our consultation on a 'UK Low Carbon Hydrogen Standard', which seeks views on the options for setting and implementing such a standard, and we intend to finalise design elements of a UK standard for low carbon hydrogen by early 2022.**

Chapter 2.5 sets out a wider range of policy and regulatory levers which we are exploring to support the development of the hydrogen economy, including production.

Our future production strategy

In most of the pathways modelled by BEIS for CB6, hydrogen demand doubles between 2030 and 2035, and continues to increase rapidly over the 2030s and 2040s. By 2050, between 250-460TWh of hydrogen could be needed across the economy, delivering up to a third of final energy consumption.[24] Current analysis suggests that in 2050, hydrogen will be supplied through a mix of steam methane reformation with CCUS, electrolysis from renewable electricity, and biomass gasification with carbon capture and storage (BECCS), a position supported by the CCC's CB6 advice.[25]

As the hydrogen economy expands and demand grows, researchers, innovators, investors and producers will respond with new technological advances that could deliver further production cost reductions or greater emissions savings. The role for other production methods, including existing and future nuclear technologies, methane pyrolysis, and thermochemical water splitting, will need to be assessed and integrated into our modelling as appropriate to give us an evolving picture of our future production mix. As we increase our understanding of the project pipeline, and the measures needed to overcome barriers to widespread deployment of a range of production technologies, we can form a better picture of our future production strategy. In doing so, we will continue to consider the wider environmental impacts of different methods of hydrogen production, such as resource requirements for land or water, or any potential changes in soil, water or air quality. The production of hydrogen is likely to need significant amounts of water and, together with industry, we will continue engaging with the Environment Agency, regional water resources groups and water companies to ensure appropriate plans are in place for sustainable water resources.

During 2021 we will gather further evidence through our consultations on a Hydrogen Business Model, the NZHF and the standard for low carbon hydrogen, and undertake additional work on our production pathway in line with CB6. This will give us a better understanding of the mix of production technologies, how we will meet a ramp-up in demand, and the role that new technologies could play in achieving the levels of production necessary to meet our future CB6 and net zero commitments. **We will develop further detail on our hydrogen production strategy and twin track approach, including less developed production methods, by early 2022.**

2.3 Hydrogen networks and storage

Key commitments

- We will launch a **call for evidence on the future of the gas system** in 2021.
- We will **review systemic hydrogen network and storage requirements** in the 2020s and beyond, including need for economic regulation and funding, and provide an update in early 2022.
- We will deliver the **£68 million Longer Duration Energy Storage Demonstration** competition.
- We will deliver the **£60 million Low Carbon Hydrogen Supply 2** competition.

The development of network infrastructure to allow low carbon hydrogen to be transported to storage points and end users is central to the expansion of the hydrogen economy. Networks for the purposes of distributing hydrogen (hereafter hydrogen networks) will include a range of pipeline and non-pipeline channels (e.g. road and rail vehicles, marine vessels) which are crucial to ensuring hydrogen can reach a full range of end users, and be a truly strategic low carbon energy source in a net zero system.

Existing hydrogen production and use in the UK is currently on a small scale, and hydrogen tends to be produced and used in the same location. There is limited distribution through hydrogen pipelines, used to supply industrial users located in industrial clusters, as well as some transport of hydrogen by road into these hubs in either compressed gaseous or liquefied form. Alongside this, there is limited use of above ground metal storage tanks in industrial facilities.

We will need to see significant development and scale up of hydrogen network and storage infrastructure for the development of a UK hydrogen economy and for low carbon hydrogen is to play its role in supporting UK decarbonisation over the 2020s, under CB6 and on a pathway to net zero.

2.3.1 Networks – hydrogen transmission and distribution

How will hydrogen networks develop and scale up over the 2020s and beyond?

Hydrogen networks will have to grow and diversify considerably over the 2020s to enable the UK to meet its 2030 ambition and prepare for ramp up to CB6 and beyond. We expect growth to be driven by production and demand. This will impact the shape and location of the network, and whether it evolves into a national system or a number of regionally-based networks. This decade will see key policy decisions taken that will influence how hydrogen networks develop and are operated. Such decisions will need to consider interplay with existing oil and gas infrastructure, CO_2 transport and storage infrastructure, and electricity infrastructure.

Strategic decisions on blending hydrogen into the gas grid and hydrogen for heating will have a significant impact on the development of hydrogen networks. Blending may result in investments in equipment and infrastructure needed to support rollout in localised portions of the existing gas networks (see Chapter 2.5.1 for further details), and the decision on the use of hydrogen for heating (see Chapter 2.4.3) will impact the nature and scale of hydrogen network scale up, including whether and the extent to which parts of the gas grid are repurposed or decommissioned in the longer-term.

By the late 2020s and 2030, with the expansion of hydrogen production to several large-scale CCUS-enabled projects and electrolytic projects at a range of sizes, the hydrogen pipeline network may span tens of kilometres in length, supplying end-users either within cluster regions or more broadly. By the mid-2030s, the hydrogen network could serve multiple end use applications extending to tens to hundreds of kilometres, potentially including hydrogen converted and distributed as ammonia for use as a shipping fuel.

Internationally, countries are considering the need for dedicated hydrogen networks, alongside conversion of existing gas infrastructure. The potential for pan-European dedicated hydrogen transport infrastructure[26] and the use of existing or new gas interconnectors between the UK and Belgium, Netherlands and Ireland may enable the UK to trade hydrogen or low carbon gas with our neighbours in the future.

As larger cluster networks expand and we have more end users and larger scale storage development, we would expect all parts of the hydrogen economy to reach technology and market maturity by 2050, with potentially national-level distribution.

How are we approaching the task?

There are several interrelated issues which we will need to consider in developing networks that can fulfil hydrogen's potential as a key enabler in decarbonising the UK energy system.

While we expect the initial growth in networks to be driven by the market and the needs of specific privately-operated projects, we believe *it will be important that initial investments and later evolution of the network are achieved in a coordinated manner*, which manages investment risks and delivers benefits to consumers while delivering our 2030 ambition and positioning the hydrogen economy for significant expected growth beyond this. We will need to consider whether and what policy mechanisms, such as incentives or regulation, are needed to ensure that network infrastructure is developed to allow later build out and interlinkages. We will also need to manage or mitigate the risk of stranded assets if pipelines developed for initial projects in the 2020s are not fit for purpose in the 2030s.

Issues around *whether and how to fund hydrogen networks* need to be considered, accounting for variables such as length of pipe, number of producers and end users, and capacity of pipe for future development. Funding considerations are likely to be different for different sizes and types of projects – for example, small scale early pipelines using new or connecting to existing small-scale infrastructure versus large scale pipelines which connect to larger network infrastructure, either new or repurposed from existing networks.

We will need to consider the *type of commercial frameworks and ownership structures* needed for end-to-end pipelines and for wider networks with many suppliers and end users. This will be particularly important when thinking about whether early commercial arrangements for the production and distribution of hydrogen will be sufficient to enable scale up of the hydrogen economy in the later 2020s, or whether changes are needed to support this. Issues related to regulating third-party access to infrastructure, monopolies and unbundling will need to be resolved to provide clarity to investors.

Decisions on where *CCUS infrastructure* will be installed will impact the development of networks for CCUS-enabled hydrogen production and vice-versa. These two policy areas will need to be co-developed to ensure optimum outcomes in both areas are achieved.

Decisions on heat and on the future of the existing gas network will have a significant impact on the size and design of hydrogen networks. While there may be efficiencies in repurposing parts of the gas network, this may not be appropriate for all parts of the country or for all end users.

We expect some *non-pipeline distribution* for areas without pipeline connections to emerge over the 2020s through trucks and other road transport, which could enable further use of hydrogen beyond production centres. We will need to understand the existing regulatory context for non-pipeline distribution and whether it is fit for purpose in an expanded hydrogen economy, as well as whether funding support would be needed.

What are we doing to deliver?

We recognise the need to put in place clear policies and supportive regulatory regimes and to build consumer acceptance to rapidly develop and deploy hydrogen networks.

There is already a range of work ongoing to explore the development of hydrogen networks. A variety of joint government and industry research, development and testing projects are underway, designed to help determine the safety, feasibility, costs and benefits of converting the existing gas grid to carry 100 per cent hydrogen (see Chapter 2.4.3). This includes identifying and characterising the possible options to transition the gas grid, including repurposing the existing grid, building new networks, or transitioning parts of the grid. This work will support strategic decisions in the mid-2020s on the role of hydrogen for heating and linkages with the existing gas grid. Other projects, such as those set out below, will also help inform the evidence base for developing hydrogen network infrastructure. **We will continue to support such research, development and testing projects to explore development of hydrogen network infrastructure.**

Exploring hydrogen network infrastructure

Project Union explores the development of a UK hydrogen network which would join industrial clusters around the country, potentially spanning 2000km. This National Grid project would repurpose around 25 per cent of the current gas transmission pipelines and could carry at least a quarter of the UK's current gas demand. The feasibility stage of the project is using net zero development funding to identify pipeline routes, assess the readiness of existing gas assets, and determine a transition plan for assets. The research will also explore how National Grid can start to convert pipelines in a phased approach from 2026.

H21 is a series of industry-led projects funded by Ofgem which test pure hydrogen in pipelines and connecting infrastructure to build the evidence base for hydrogen transport in dedicated pipelines. The findings from these programmes are being used to establish frameworks for pipeline safety which will be appraised by the HSE's Science Division, and help inform government's strategic decision on the longer-term role of hydrogen for heat by the mid-2020s (see Chapter 2.4.3).

FutureGrid aims to create a representative transmission network to trial hydrogen. The network will be built from a range of decommissioned transmission assets and will allow for real-time testing and analysis of the network in operation. Blends of hydrogen up to 100 per cent will be tested at transmission pressures to assess how the re-purposed assets perform, with construction to launch this year and testing in 2022. FutureGrid will connect to Northern Gas Network's existing H21 distribution network facility and the HyStreet homes to demonstrate that a complete 'beach-to-meter' network can be decarbonised. This £12.7million National Grid project is largely funded through Ofgem's Network Innovation Competition (£9.1 million) with the remaining amount from project partners. To allow testing to be undertaken in a controlled environment with no risk to the safety and reliability of the existing gas transmission network, the hydrogen research facility will remain separate from the main National Transmission System.

Future Billing Methodology is a Cadent Gas project to explore a range of different options for future gas billing to prepare for potential changes to gas blends. Future consumer gas billing methodologies will need to reflect the differences in calorific value between methane, biomethane and hydrogen to enable blending of these gases into the existing grid.

The Iron Mains Risk Reduction Programme decommissions gas distribution iron mains and replaces them with new plastic ones, which are potentially well-suited for transporting hydrogen within the existing gas grid over the long term. This project was introduced in 2002 and is regulated by the HSE.

We will also consider whether the costs of small-scale distribution infrastructure and connecting to existing networks operated by third parties could be factored into overall project costs of production under the proposed hydrogen business model. We expect that this model is unlikely to be appropriate for large scale projects or pipelines which form part of a larger network infrastructure, and we will need to explore whether funding for these larger projects is appropriate and what that might look like. **We will use the Hydrogen Business Model Consultation published alongside this strategy to seek views on a limited number of questions which will feed into the design of the business model and the hydrogen network review set out below.**

Beyond testing and evidence-building, we anticipate that work to explore investment signals and necessary amendments to legislation, regulatory frameworks and potential access to financing for hydrogen network projects in the early 2020s and the 2030s will be required. This will need to address issues such as:

- Uncertainties around the permitting procedures (and accompanying regulations) for new hydrogen pipeline infrastructure, which could be located in hydrogen supply hubs initially before wider network expansion.
- Potential need to further harmonise regulations between new hydrogen pipelines in clusters and existing hydrogen pipelines.
- How to provide sufficient flexibility for any future regulation of end use applications involving domestic consumers such as heating.

In the 2020s, we will seek to ensure that an appropriate legislative framework is in place to incentivise investment in resilient, efficient infrastructure, which integrates low carbon energy solutions over time. As part of this, **we will review the overarching market framework set out in the Gas Act 1986 to ensure appropriate powers and responsibilities are in place to facilitate a decarbonised gas future. We are also reviewing gas quality standards with a view to enabling the existing gas network to have access to a wider range of gases.** This will potentially include hydrogen, subject to hydrogen blending trials proving successful.

We will launch a Call for Evidence on the future of the gas system this year. Amongst other things, the Call for Evidence will look at the current gas types, including implications for a potential increased use of hydrogen in the system, and will seek to include questions on the potential role of hydrogen in the existing gas system. The outcome of the Call for Evidence should draw out expertise on gas across the energy sector, gather views from stakeholders and the public around the future role of gas in meeting our net zero target, highlight concerns that need to be addressed, including risks and barriers, and collect evidence on work currently being done by industry on the future role of the gas system that focuses on the net zero ambition.

We recognise the need for further detailed work to establish the policy approach for the development of hydrogen network infrastructure and the decisions to be taken over the course of the 2020s. In doing so, we will seek to identify where decisions and action can be taken quickly so as not to stifle progress driven by the market. We will work with key stakeholders including producers, network operators, regulators, local authorities and end users to consider the trade-offs between different models for the expansion and diversification of hydrogen networks, while taking into account a range of related policy decisions such as decisions on decarbonising heat and use of hydrogen in transport.

Building on work already underway, **we will undertake a review of systemic hydrogen network requirements in the 2020s and beyond**, including: whether funding or other incentives are needed; introduction of regulation specific to hydrogen networks; resilience and future-proofing ahead of potential regional and national networks; and interaction with wider networks including CCUS,[27] gas and electricity. We will develop policy in this area in several ways, including through discussion and consultation with the Hydrogen Advisory Council and its working groups, and the Hydrogen Business Model consultation published alongside this strategy. While we recognise that there is important learning to be drawn from existing regulatory models and the technical assessments that are being progressed by incumbent parties, we will not make assumptions about who owns and operates hydrogen pipelines, nor how these networks are governed, which will form part of the critical evidence appraisal. We will use the Hydrogen Business Model consultation to seek early views on some of these questions. **We will provide information on the status and outputs of this hydrogen network review in early 2022**.

2.3.2 Hydrogen storage

Hydrogen's ability to store energy for long periods of time and in large quantities is an important part of its strategic value to a fully decarbonised energy system, and we envisage hydrogen storage being a key part of future network infrastructure. Storage can support security of supply as production and use increase and become more spread over time and distance. Similarly, for a future energy system with a lot of intermittent renewable

power generation, hydrogen could be an important storage medium, converting excess renewable energy into a fuel for use across the economy, and supporting faster and greater integration of renewable capacity and the transition to a fully decarbonised power system (see Chapter 2.4.2).

There are a number of ways in which hydrogen can be stored:

- **Specialist tanks or storage vessels** can store MWh of energy, be stationary or mobile (such as tube trailers), and are purpose built using materials able to hold hydrogen at pressure.[28] These are already used in the chemicals industry and at hydrogen refuelling stations. Storage vessels have lower upfront costs than other methods, and are quicker to install or deploy; these may be attractive to projects seeking to balance their own supply and demand by storing lower volumes of hydrogen, or for use in areas without wider infrastructure, such as use of industrial non-road vehicles on construction sites.

- **Salt caverns (underground) storage** can store TWh of energy and are created by 'solution mining', where water is used to dissolve an underground space in a seam of rock salt, allowing hydrogen to be piped in and out. Hydrogen has been stored in caverns under Teesside since the 1970s,[29] and there is potential to repurpose caverns currently used for storing natural gas. The British Geological Survey suggests we have significant rock salt formations with potential for 1000s of terawatt hours of future storage.[30] Underground storage is able to provide large volume storage at lowest cost per unit of energy stored.[31] This is a significant strategic advantage for the UK compared to many other countries.

- **Depleted gas or oil fields (undersea) storage** while available in the UK, require further testing to be used for hydrogen. We will also need to consider competing storage demands, notably for CO_2, in these fields.

- **Hydrogen carriers (ammonia (NH_3), liquid organic hydrogen carriers (LOHCs, such as toluene), cryogenic liquid, substances such as metal hydrides)** provide a route to store energy from hydrogen at increased energy density. These storage methods may become more widely used as research and innovation reduces associated costs, complexity and efficiency losses.

Hydrogen storage in a net zero energy system

Storage can support the hydrogen economy in a range of ways that position it as a strategic asset not just for hydrogen, but as part of a fully decarbonised, net zero economy by 2050.

Most hydrogen today is produced and used directly in industrial processes, often with one operator overseeing both operations, largely removing the need for storage. However, as hydrogen takes on a wider role across the energy system and production methods evolve, storage may become more important to allow balancing within larger projects and to enable the hydrogen economy to develop in the most technically and economically efficient way, helping to manage swings in demand and supporting the transfer of energy across sectors and time.

Storage may be more important for hydrogen than it is today for natural gas because there are no natural reserves of hydrogen that can be relied upon at times of high demand. Hydrogen has to be manufactured, and there are optimal ways of doing so, including maintaining steady production across time. Storage can support this.

Storage could help the early development of the hydrogen economy where demand takes time to build or if there is change in the profile and nature of off-takers. Over time, should we see large scale use of hydrogen in heat, strategic underground storage would be highly valuable in meeting seasonal demand variations, and as discussed above, it may play an important role in smoothing the intermittency of renewable energy.

National Grid's 'Future Energy Scenarios 2021' suggest that between 12TWh and 51TWh of hydrogen storage will be required in 2050 across varying net zero compliant scenarios.[32] Similarly, Aurora Energy Research's 'Hydrogen for a Net Zero GB' report concludes that 19TWh of centralised salt cavern storage might be required by 2050.[33] The UK currently has seven salt caverns and depleted gas fields being used as active natural gas storage facilities, providing approximately 1.5 billion cubic meters, or 145TWh, of storage capacity.[34] Although some of this could be repurposed for hydrogen storage, providing the same level of energy storage as hydrogen would require greater capacity given that hydrogen has only a third the energy density of natural gas.

How will hydrogen storage scale up in the 2020s?

In the early 2020s, hydrogen storage vessels are likely to be the most common storage option, used for example at hydrogen refuelling stations coupled to electrolytic hydrogen production. In the mid-2020s, CCUS-enabled production for industrial fuel switching is likely to be designed to minimise supply-demand variations, as is the case on clusters today. Proposed cluster projects in development such as HyNet North West[35] and Zero Carbon Humber have identified local large scale underground storage options but these appear to be secondary phase needs.[36]

Case study: SSE Thermal and Equinor hydrogen storage facility

SSE Thermal and Equinor are developing plans for one of the world's largest hydrogen storage facilities at Aldbrough on the East Yorkshire coast. The project partners believe the facility could be storing low carbon hydrogen as early as 2028. With an expected capacity of at least 320GWh in the first phase, Aldbrough Hydrogen Storage would be significantly larger than any hydrogen storage facility in operation in the world today. The existing Aldbrough Gas Storage facility commissioned in 2011 holds 40 per cent of the UK's gas storage capacity in its nine underground salt caverns, each roughly the size of St. Paul's Cathedral. Upgrading the site to store hydrogen would involve creating new caverns and/or converting the existing caverns.

The Aldbrough site is ideally located to store the low carbon hydrogen set to be produced and used in the Humber region, where Equinor and SSE Thermal are developing large-scale hydrogen projects as part of the Zero Carbon Humber partnership.

Equinor has announced its intention to develop 1.8GW of blue hydrogen production in the region, while the two project partners have plans to develop the world's first major 100 per cent hydrogen-fired power station by the end of the decade in Keadby, North Lincolnshire. The Aldbrough facility will initially store the hydrogen produced for the Keadby power station, and hopes to support and enable growing hydrogen ambitions across the region, supplying an expanding diverse off-taker market including power, heat, industry and transport throughout the late 2020s and 2030s.

By the late 2020s, a town-scale pilot of hydrogen heating and the potential for hydrogen in power generation could increase the necessity of large scale storage such that underground facilities start to become important. We may also see some initial volumes of hydrogen converted and stored as ammonia for use in shipping by the end of the decade, with increased scale up in the 2030s.[37]

Where early storage needs are limited to above ground storage vessels connected to specific production and use, we anticipate that projects could receive sufficient support from our proposed Hydrogen Business Model or the Renewable Transport Fuel Obligation to meet associated storage costs. However, as larger scale storage becomes required and the market develops, storage-specific revenue support could be needed.

Developing large-scale hydrogen storage, particularly as a strategic asset, will require overcoming significant challenges, in particular:

- Understanding the optimal need for, pace of development and mix of hydrogen storage technologies. This is dependent upon multiple factors, some of which are uncertain, such as routes to fully decarbonise power and heat.

- Long lead times and complexity in strategic scale storage such as salt caverns and depleted oil and gas fields. Salt caverns can take up to ten years to develop with challenges such as the need for environmentally appropriate disposal of brine. Repurposing depleted oil and gas fields will require understanding of demand for storage at scale and planned decommissioning dates if investment is to be made to extend the life of assets.

- Need for significant levels of investment, with salt caverns costing potentially hundreds of millions of pounds to develop. Further work is needed to understand the need for and potentially develop suitable funding mechanisms to support this.

- Further research and innovation to increase the efficiency for hydrogen storage, develop the viability of more energy dense options at a variety of scales, and understand the safety and environmental impacts of different storage options.

What are we doing to deliver?

Government is committed to supporting research and innovation to enable hydrogen storage to fulfil its potential in the future energy system. We have supported hydrogen storage through the £33 million Hydrogen Supply Competition,[38] provided UKRI funding to support innovation from industry such as Project Centurion[39] (a hydrogen salt cavern storage demonstration project), and are discussing proposals from industry to store hydrogen in depleted gas fields and storage facilities.

Building on these early developments, **we recently launched an expression of interest for the £60 million Low Carbon Hydrogen Supply 2 competition.**[40] Similar to the first competition in 2018, this is an innovation competition open to support a range of demonstration projects including hydrogen storage technologies, alongside wider hydrogen supply solutions. **We have also launched our £68 million Longer Duration Energy Storage Demonstration competition,**[41] which aims to accelerate commercialisation of innovative longer duration energy storage projects at different technology readiness levels. Storing hydrogen produced from excess electricity as a means of providing key flexibility services to the UK power grid is included within the scope of the proposal, subject to eligibility criteria.

More broadly, understanding the views of industry and developing our understanding of possible storage needs in different hydrogen scenarios over time will be key to realising the potential of hydrogen storage. We recently published a *Call for Evidence on facilitating the deployment of large-scale and long-duration electricity storage*[42] seeking views from industry on the barriers that electricity storage technologies face, including hydrogen where this is used in the power system.

To build on this evidence including beyond the electricity system, **we will undertake a review of systemic hydrogen storage requirements in the 2020s and beyond, including its potential role as a critical enabler for some end use sectors.** The review will consider whether funding or other incentives are needed, whether further government regulation might be required to ensure that the necessary storage infrastructure is available when needed, and what form this might take. Working with technology developers, regulators, and other stakeholders via the Hydrogen Advisory Council and other forums, and informed by our consultation activities, this work will inform future government policy on storage. In the meantime, **the Hydrogen Business Model consultation that accompanies this strategy includes specific questions on the treatment of small-scale storage within the Hydrogen Business Model, as well as on the potential need for government intervention to facilitate investment in future larger scale storage.** Answers to these questions will help inform our storage review. **We will provide information on status and outputs of this review in early 2022, to facilitate further discussion with stakeholders.**

There is still much work to do to understand, develop and scale up the network and storage infrastructure required to support a thriving UK hydrogen economy and position hydrogen to support the wider decarbonisation of the energy system by the end of the decade. Getting it right will be help deliver our 2030 production ambition and contribute to emissions reduction across end use sectors, helping to achieve CB6 and put the UK on a pathway to net zero. Government will continue to work closely with industry, regulators, consumers and the research and innovation community over the coming months and years to make sure that we do.

2.4 Use of hydrogen

Key commitments

- We will launch a call for evidence on **'hydrogen-ready' industrial equipment** by the end of 2021.
- We will launch a call for evidence on **phase out of carbon intensive hydrogen production in industry** within a year.
- We will deliver Phase 2 of the **£315m Industrial Energy Transformation Fund**.
- We will launch a **£55 million Industrial Fuel Switching 2 competition** in 2021.
- We will prepare for hydrogen for heat trials – a **hydrogen neighbourhood by 2023**, **hydrogen village by 2025** and **potential pilot hydrogen town by 2030**.
- We aim to consult in 2021 on **'hydrogen-ready' boilers** by 2026.
- We will continue our **multi-million pound support for transport decarbonisation**, including for deployment, trials and demonstration of hydrogen buses, HGVs, shipping, aviation and multi-modal transport hubs.

As set out in Chapter 1, low carbon hydrogen will have an important complementary and enabling role alongside clean electricity in decarbonising our energy system, with potential to help decarbonise heavy industry and provide greener, flexible energy across power, heat and transport. The roadmap in Chapter 2.1 shows how we expect use of hydrogen across the economy to develop over the course of the 2020s and beyond, with early demonstration in industry, heat and power and limited use in transport applications in the earlier part of the decade developing into a wide range of uses across multiple sectors by the late 2020s and into the mid-2030s under CB6.

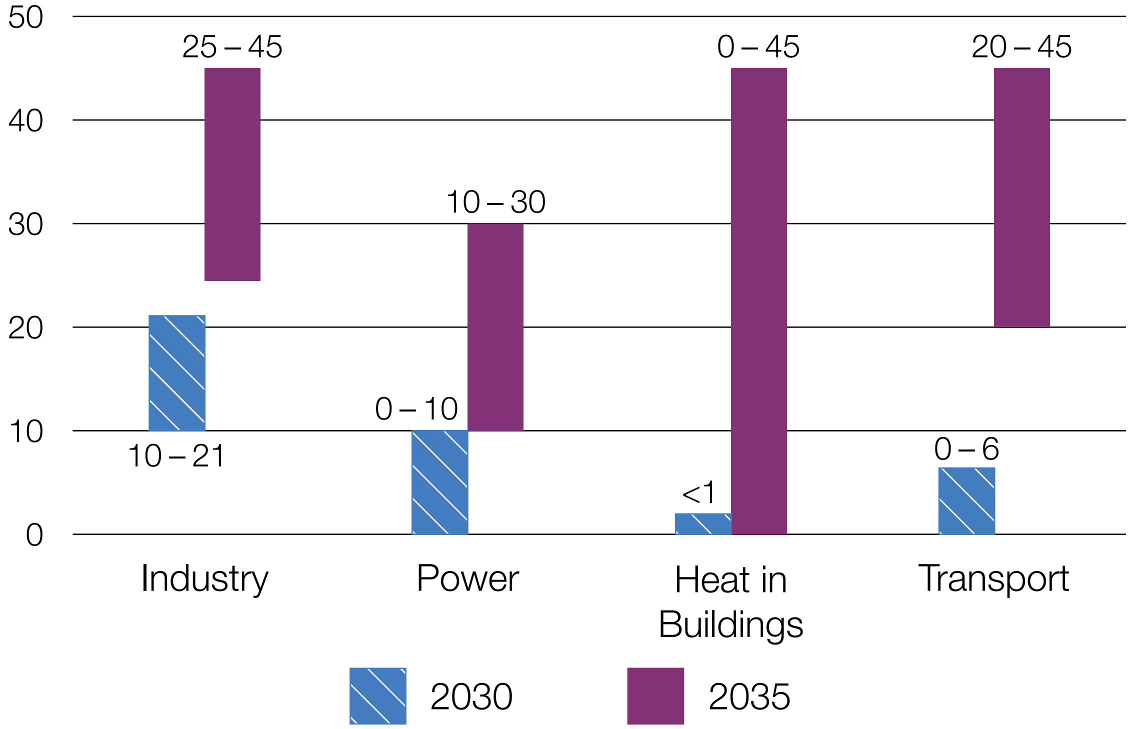
Unlocking the use of low carbon hydrogen can support efforts to deliver against many of the outcomes set out in Chapter 1.5, including decarbonising existing UK hydrogen production and use, establishing end-to-end systems with a diverse range of end users,

and supporting emissions reductions under CB4 and 5. The shift from fossil fuels to hydrogen can also be beneficial for the environment, including for air quality, although the extent of these benefits will depend on the mix of hydrogen technologies deployed. As such, deployment of hydrogen will need to consider these wider environmental costs and benefits.

In line with our strategic principles, we will support research, innovation and commercialisation of hydrogen technologies across a wide range of end uses, alongside testing and at-scale deployment, to help overcome the barriers facing low carbon hydrogen alternatives while allowing the market to determine the optimal technology mix. In doing so, we are aware that current early markets, for example road and depot-based transport, may differ from those where we expect hydrogen to play a more significant role in the longer term, such as in heavy industry. Our roadmap will help us design policy that encourages early use cases while bringing forward applications with the greatest strategic potential to support deep decarbonisation of the UK economy.

The state of current technology development, characteristics of hydrogen in relation to other low carbon energy sources and potential for cost reductions provide some indication of how the use of hydrogen in the UK is likely to develop in the near- to medium-term. Our analysis suggest potential hydrogen demand of up to 38TWh by 2030 split across sectors, not including use of hydrogen for blending into the gas grid. This could rise to 55-165TWh by 2035 under CB6 (see Figure 2.4 below).

Figure 2.4: Illustrative hydrogen demand in 2030 and 2035



Source: BEIS analysis (see analytical annex). Note: figures do not include blending into the gas grid.

We expect that industry will form a lead option for both early hydrogen use and in the longer term, with demand from hydrogen fuel switching picking up from the middle of this decade and hydrogen playing a key role in further decarbonisation of industry by the mid-2030s under CB6 and on the pathway to net zero.

Hydrogen is likely to play an important enabling role in a fully decarbonised power sector, through the system flexibility that electrolytic production and hydrogen storage can provide and the potential for flexible power generation using hydrogen as a fuel – helping to balance a more variable renewables-based electricity grid. We could see use of hydrogen in power in this way by the late 2020s with further scale up by the mid-2030s.

Hydrogen could also provide an important low carbon alternative – alongside electrification – to the UK's largely natural gas-based domestic heating sector, and government is supporting major studies and testing projects, including first-of-a-kind heating trials, to fill important evidence gaps on the costs, benefits and feasibility of using hydrogen for heating. This will be used to inform broader strategic decisions on heat decarbonisation in the middle of this decade. We are also exploring the option of blending hydrogen into the gas grid, with a decision to be taken in 2023 following testing of the safety, technical and economic case (see gas blending box in Chapter 2.5).

Finally, hydrogen is likely to be fundamental to achieving the full decarbonisation of transport, with particular potential in areas of heavy transport 'that batteries cannot reach'. Hydrogen buses are already in use in some UK towns and cities, and feasibility studies are underway for the use of hydrogen and other zero emission technologies in heavy goods vehicles (HGVs) with the aim of undertaking future years trials (subject to funding). We expect hydrogen to play a significant role in decarbonising international shipping and aviation, with demonstration and trials already underway, potential for early stage uses in shipping and aviation by the end of the decade, and an increasing role from the 2030s.

Given the wide range of applications and the strategic enabling role that hydrogen can play in an increasingly decarbonised economy, the 2020s will be critical to developing, testing and scaling up the use of low carbon hydrogen in the UK. The following sections set out how government and industry will work together to unlock the potential that hydrogen holds to decarbonise these important UK sectors.

2.4.1 Use of hydrogen in industry

It is clear that UK industrial sectors will play a vital role in developing a hydrogen economy over the next decade. Industry produced 16 per cent of UK emissions in 2018,[43] and hydrogen will be critical to decarbonise industrial processes that would be hard to abate with CCUS or electrification. The *Industrial Decarbonisation Strategy* published earlier this year sets out the policy and technology principles to decarbonise industry by 2050, including the installation of deep decarbonisation infrastructure such as hydrogen and CCUS networks in the 2020s.

Our industrial heartlands will likely lead the way for large scale low carbon hydrogen supply, and industrial users are expected to provide the most significant new demand for hydrogen by 2030 through industrial fuel switching. Today's hydrogen economy will need to scale up from its current base in the oil refining and chemical sectors, to enter other parts of industry and the wider energy system. We will develop policy to support and deliver this change, and to drive the decarbonisation of existing industrial hydrogen use.

Decarbonising current hydrogen production and use in industry

To meet our net zero ambition and develop the new low carbon hydrogen economy, we need to decarbonise existing industrial production of carbon intensive hydrogen. Today, hydrogen is mainly produced by steam methane reformation (without CCUS) for use as a feedstock, or as a by-product of other industrial processes. The most appropriate option to decarbonise existing production will vary for different types of industrial sites and will depend on factors such as the life cycle of current assets and the production method used. As the oil refining and chemical sectors are today often both producers and consumers of hydrogen, they could be important drivers of the transition to a low carbon hydrogen economy.

We will support hydrogen producers to decarbonise through, for example, the Industrial Carbon Capture and Hydrogen Business Models. Furthermore, we will finalise the design elements of a UK standard for low carbon hydrogen by early 2022.

We will also publish within a year a call for evidence to explore with industry the further interventions needed to phase out carbon intensive hydrogen and transition to low carbon production methods and sources, at the required pace to meet net zero.

Switching to low carbon hydrogen as an industrial fuel

Low carbon hydrogen can also provide an alternative to natural gas and other high carbon fuels currently used for industrial heating. This includes both indirect heating applications,

for example, using hydrogen to fuel steam boilers and combined heat and power (CHP) systems, and direct heating processes, such as melting glass in a furnace. Low carbon hydrogen is a good option for processes that are more expensive or harder to electrify, given its potential to replace natural gas.

The *Industrial Decarbonisation Strategy* set out that we expect, at a minimum, 20TWh per year of fossil fuel use to be replaced with low carbon alternatives, including hydrogen, electrification and biofuels, in 2030. Our latest analysis suggests that by 2030 demand from industry for low carbon hydrogen as a fuel could range from around 10TWh per year if supply is limited to clusters, up to around 20TWh per year if some dispersed sites are connected to pipelines.[44] Further demand could be realised from sites sourcing hydrogen from local electrolytic production. Fuel switching to low carbon hydrogen could yield carbon savings of around 3MtCO_2e per year by 2030, equivalent to taking 1.4 million cars off the road.

To meet CB6, we anticipate that industrial demand for low carbon hydrogen would need to continue to grow, reaching up to 45TWh by 2035. This increase would be driven by a growing number of sites with access to low carbon hydrogen, continued technology development to expand the range of processes capable of using hydrogen, and a shift in associated costs, such as the price of carbon, to make hydrogen an increasingly competitive fuel option. By 2050, in a scenario with widespread access to low carbon hydrogen across the UK, consumption in industry could be as high as 105TWh by 2050.

This strategy covers the full range of UK industrial sectors: metals and minerals, chemicals, food and drink, paper and pulp, ceramics, glass, oil refineries, and less energy-intensive manufacturing.[45] The greatest potential demand for low carbon hydrogen in 2030 arises from sectors such as chemicals and steel.

As set out in the *Industrial Decarbonisation Strategy*, decarbonising the steel sector will be essential to the decarbonisation of UK industry. The main options for doing so include using electric arc furnace technology coupled with hydrogen direct reduced iron, or CCUS. In collaboration with the Steel Council, we are considering the implications of the recommendation of the CCC to "set targets for ore-based steelmaking to reach near-zero emissions by 2035" and will provide an update in the forthcoming Net Zero Strategy.

Hydrogen could also be used to help abate the 6MtCO_2 emissions associated with the use of industrial non-road vehicles such as excavators and diggers used in a range of sectors. Machinery manufacturers are already developing equipment capable of using hydrogen, which alongside electrification may be an important way to decarbonise this sector. The adoption of hydrogen as a solution will depend on the development of wider hydrogen infrastructure.

We recognise that industry faces several barriers in fuel switching to low carbon hydrogen, even where it may offer the best decarbonisation option. These include the higher cost of low carbon hydrogen supply compared with fossil fuels; the capital cost of retrofitting or replacing equipment to be hydrogen-ready; the operational disruption of conversion and the subsequent costs associated with optimising new processes using hydrogen; and the operational risks associated with the security of supply of low carbon hydrogen, particularly in the short term while the market develops.

Demonstrating the technical performance of hydrogen, without compromising process efficiency or product quality, is also essential. As hydrogen has a distinct chemical composition and physical characteristics compared to current fuels, further research and testing will be needed in the 2020s. This will help industry to better understand how hydrogen transfers heat, how to limit any pollutants released during combustion (including NOx) and how this might impact materials and end products. In practice this will involve building on existing research with more lab-based studies, followed by at scale trials for distinct industrial processes.

What are we doing to deliver?

Given the scale of industrial emissions and the likely importance of hydrogen in replacing high-carbon fuels used in industry, it is critical that we demonstrate and scale up fuel switching to low carbon hydrogen on industrial sites during the 2020s. Government is already providing a range of funding opportunities that could support industry to switch to low carbon technologies including hydrogen, which complement the existing academic and private sector led initiatives in this area:

- The **£315 million Industrial Energy Transformation Fund** is supporting the uptake of technologies that improve efficiencies and reduce the carbon emissions associated with industrial processes. Hydrogen projects, subject to contract, were supported as part of Phase 1 of the competition.[46] The Fund aims to de-risk key technologies including hydrogen fuel switching by providing support for feasibility and engineering studies, and capital support for first movers to upgrade their industrial equipment. It will increase readiness for the hydrogen economy by building demand for hydrogen in industry and helping to develop the commercial case for low carbon hydrogen projects.

- The **£20 million Industrial Fuel Switching Competition** has allocated innovation funding to stimulate early investment in fuel switching processes and technologies. It has been highly successful in progressing the development of new fuel switching technologies across a range of sectors, including cement, refineries, glass and lime. The latest round of funding was awarded in winter 2019, with four projects moving from feasibility studies to demonstration, including the Mineral Products Association's world first demonstrations of firing hydrogen at commercial fuel supply scale for the manufacture of cement and lime.

- The **Green Distilleries Fund is providing £10 million of new innovation funding** to help distilleries go green. The programme is taking a portfolio approach and aims to fund a range of different solutions which could include electrification, hydrogen, biomass or waste. Nine of the 17 feasibility studies funded at Phase 1 are for projects using low carbon hydrogen.

Case study: Unilever demonstrates a hydrogen-fired industrial boiler

As part of the BEIS funded HyNet Industrial Fuel Switching competition, Unilever, working alongside Progressive Energy, is running a trial to switch an onsite natural gas fired boiler to hydrogen. The boiler, located at the Port Sunlight facility on the Wirral, raises steam needed for the manufacture of home and personal care products.

Switching to low carbon hydrogen allows the site to cut carbon emissions, with no change to manufacturing operations. This trial will provide Unilever with the evidence and confidence to convert existing boilers to run on low carbon hydrogen, once a supply is available. It seeks to demonstrate consistent steam production at the required temperature and pressure, reliable boiler operations, and adherence to NOx emissions limits.

Following successful trials on a representative boiler system at Dunphy Combustion's test site in 2021, a new 7MWth dual fuel (hydrogen and natural gas) burner will be installed in Unilever's boiler. The proportion of hydrogen fuel gas will be increased from 0 to 100 per cent over four days, with verification of steam quality and NOx emissions performance taking place, followed by several weeks of 100 per cent hydrogen firing for up to eight hours a day, providing steam for the Port Sunlight works.

Building on these successes, later this year we will launch a number of further funds to support industry to switch to hydrogen and other low carbon fuels:

- **We will provide further grant funding to support fuel switching technologies, including low carbon hydrogen, through Phase 2 of the £315m Industrial Energy Transformation Fund.**

- **We will launch a new £55m Industrial Fuel Switching 2 Competition to develop and demonstrate innovative solutions for industry to switch to low carbon fuels such as hydrogen.**

- **We will launch a new £40 million Red Diesel Replacement Competition to fund the development and demonstration of innovative technologies that enable Non-Road Mobile Machinery (NRMM) used for quarrying, mining, and construction to switch from red diesel to hydrogen or other low carbon fuels.**

Throughout the early 2020s, we will also be supporting the engineering and technical design elements of decarbonisation projects across the UK's industrial clusters through UKRI's **Industrial Decarbonisation Challenge**, to accelerate the deployment of technologies such as CCS and hydrogen fuel switching.

Building on this substantial existing industrial decarbonisation support, we will need additional dedicated support for fuel switching to hydrogen, including for further research and innovation, and demonstration and deployment of early use cases in the 2020s. To accelerate fuel switching to low carbon hydrogen, **we will seek to support research and innovation through the existing Net Zero Innovation Portfolio and initiatives led by the Industrial Decarbonisation Research & Innovation Centre (IDRIC). We will also**

engage with industry later this year on possible requirements for a research and innovation facility to support hydrogen use in industry and power.

Due to infrastructure requirements, demand will likely be concentrated in large industrial clusters during the 2020s, a significant proportion of which could arise from a small number of sites. These sites could act as 'pathfinders', proving the viability of hydrogen as a fuel at commercial scale, and helping to foster an initial market for low carbon hydrogen close to supply. **We will work with cluster projects to better understand the opportunities that pathfinder sites present, so to maximise the benefit to the sites themselves and the associated clusters.**

Initially, hydrogen will likely be used to fuel indirect heating technologies such as steam boilers and CHP units. Given the range of sectors that use steam as part of an industrial process, our analysis indicates that boilers and CHPs could make up around two thirds of demand for hydrogen fuel switching by 2030. We will therefore focus on policies to unlock the fuel switch potential for these technologies, taking into account replacement cycles of existing equipment. Work is ongoing to establish the role of hydrogen in decarbonising CHPs, and **by the end of this year we will launch a new call for evidence on 'hydrogen-ready' industrial equipment.**

Later in the decade, hydrogen could replace methane in different parts of the gas grid, either partially through blending or fully with 100 per cent hydrogen (see Chapter 2.5 for further detail on blending). Among the current users of the gas network, industry has the most variation in terms of types of equipment and uses of natural gas. Government is working with industry and with regulators to identify the changes that would be necessary to transition to full or blended hydrogen in the gas grid, and how this could impact industrial settings. **We will work with industrial end users to ensure their needs and the potential impacts of a full or partial transition to hydrogen via the gas grid are well understood.**

Collectively, this extensive set of measures will help UK industrial sectors better understand the challenges and opportunities of switching to low carbon hydrogen. Unlocking demand for low carbon hydrogen in industry will deliver significant carbon savings and help scale up the hydrogen economy. Demand from industry can act as an anchor to stimulate production, which will in turn help decarbonise other end use sectors in both industrial clusters and dispersed sites across the UK.

2.4.2 Use of hydrogen in power

As set out in the *Energy White Paper*, government is aiming for a fully decarbonised, reliable and low-cost power system by 2050, which will require the rapid growth in renewables which has been a key driver of emissions reductions to date. To meet CB6 on the way to this, we must aim for a largely decarbonised power sector by the mid-2030s. Deployment of renewables and other forms of low carbon generation is projected to further scale up, demand for electricity will increase as more sectors shift to electrification, and power generation will become more decentralised, variable and intermittent as we become increasingly dependent on wind and solar. To support this transition, we will need more flexible, low carbon generation and flexible technologies such as energy storage and demand-side response to manage demand peaks and to balance electricity supply and demand.

Low carbon hydrogen can play an important strategic role in meeting these future power system needs, and developing and scaling hydrogen in power during the 2020s can reduce the burden on other technologies such as renewables, CCUS and nuclear. While not a 'silver bullet', there are two key roles that hydrogen could play in the power system:

- **Flexible power generation** ('Gas to Power'): Low carbon hydrogen can play an important role in providing flexible power generation such as such as through rapid operating 'peaker' plants and larger scale but less flexible Combined Cycle Gas Turbines (CCGTs), helping to meet short- and longer-term peaks in demand. This hydrogen could be used either as a blend or at 100 per cent and would be supplied by pipeline or through access to storage. Our analysis[47] indicates that by 2030, we could see a small but important role for low carbon hydrogen to generate power, with demand for hydrogen in power ranging from 0-10TWh. We expect to see further ramp up beyond 2030: hydrogen demand could increase to 10-30TWh in 2035, and 25-40TWh by 2050. Using hydrogen in this way could also play a role in establishing secure offtake for hydrogen production projects in the near term.

- **System flexibility through electrolysis and storage** ('Power to Gas', 'Power to Gas to Power'): Electrolytic hydrogen production can also provide grid flexibility by drawing on 'excess' renewable or low carbon electricity that would otherwise be constrained or curtailed (where power cannot be transmitted) and where there is an economic case to do so. In this way electrolytic hydrogen can allow excess electricity to flow across different parts of the system, from power to gas, to transport or industry (often referred to as 'sector coupling'). This unlocks a wide range of system benefits and can provide an additional route to market for new and existing renewables capacity. Coupling this electrolytic production with storage, including long duration storage where hydrogen is a lead option (see Chapter 2.3.2), can help integrate hydrogen further into our power system by helping to balance the grid when generation from renewables is higher or lower than demand.

How will we develop and scale up hydrogen in power over the 2020s?

Use of hydrogen in power will need to rapidly scale up through learning by doing in the 2020s to support further decarbonisation by the 2030s and to realise this strategic role in a fully decarbonised power sector in the long term.

From the mid-2020s, as demand for flexible power generation increases, we expect hydrogen blends to be the primary use of hydrogen in the power sector, shifting to the first 100 per cent hydrogen turbines later in the decade. At smaller scales, we could see hydrogen fuel cells playing a role, replacing high carbon alternatives such as diesel generators to provide flexibility and backup generation for off grid locations and in cities, building on limited deployment to date. From 2030, we expect that low carbon hydrogen, and potentially ammonia (subject to meeting air quality and emissions standards), will play an increasing role in providing peaking capacity and ensuring security of supply.

As the need for flexibility and renewables deployment increases out to 2030, we expect to see increasing deployment of electrolyser capacity, both contributing to delivering our 5GW ambition and supporting decarbonisation of power and other sectors where there is an economic case to do so. The 2020s will be focused on deploying a future generation of electrolysers which will be larger and better adept at operating variably in line with renewables. Throughout the 2020s and out to 2030 we anticipate long duration hydrogen storage coming online and scaling up, integrating hydrogen into our power system and coupled with flexible generation where this is needed.

To achieve this integration of hydrogen in the power sector by 2030, we will need to tackle the key barriers to deployment in the early part of this decade:

- *Technology and user readiness:* We need to demonstrate a range of technologies across the hydrogen value chain, including next-generation electrolysers, large scale hydrogen storage, and 100 per cent hydrogen turbines, which are not yet commercially available in the UK. We also need to ensure hydrogen or ammonia firing is aligned to wider emissions standards. Secure availability of hydrogen will be critical to addressing this barrier.

- *Designing supporting policy and market frameworks:* We need to better understand the role of hydrogen across the power system, and drive investment in hydrogen power applications alongside hydrogen production, primarily through existing or planned policy frameworks to help unlock demand in the power sector.

- *Availability of networks and storage:* The location of hydrogen power generation and system flexibility in the 2020s and out to 2035 will in part be driven by the availability of hydrogen network and storage infrastructure, including non-pipeline distribution for smaller scale applications.

What are we doing to deliver?

There are currently few examples of low carbon hydrogen use in the power sector, despite hydrogen technologies being eligible to participate in electricity markets including the Capacity Market and balancing services, some fuel cells and turbines already being capable of accepting hydrogen, and testing underway to commercialise 100 per cent hydrogen turbines at larger scales. The Industrial Decarbonisation Challenge is also supporting the development of hydrogen power generation as part of wider cluster proposals.

In light of this, government has recently undertaken a series of actions to better understand the role of, and the support needed for, hydrogen in power, including:

- Publishing our **Modelling 2050 - Electricity System Analysis report**[48] alongside the Energy White Paper in December 2020 which focused on building our evidence base to better understand the implications of net zero on our power system, and included exploring the potential role of hydrogen in our changing energy system.

- Publishing a **Call for Evidence on enabling a high renewable, net zero electricity system** in December 2020,[49] which explored options to evolve the current Contracts for Difference (CfD) mechanism for future allocation rounds, including coupling of technologies that can deliver increased flexibility, such as electrolysis.

- Publishing a **Call for Evidence on 'Decarbonisation Readiness' for new power generation** in July 2021,[50] which sought views on removing the 300MW threshold and expanded the technology types covered to the majority of combustion equipment. The proposals include hydrogen conversion as an alternative decarbonisation route alongside CCUS. New build plants would need to be capable of accepting either hydrogen blends of 20 per cent or be 'CCUS ready' from initial operation. From 2030, plants would be expected to be capable of accepting 100 per cent hydrogen.

- Publishing a **Call for Evidence on facilitating the deployment of large-scale and long-duration electricity storage**, in July 2021,[51] which sought views on barriers that electricity storage technologies face, including information regarding hydrogen technologies that are used in the power system.

- Publishing **Capacity Market 2021: a Call for Evidence on early action to align with net zero** in July 2021,[52] particularly focusing on actions to bring forward more low carbon capacity in the future such as hydrogen-fired generation.

In addition to this evidence gathering activity, we recognise the need to take further concrete and coordinated action now to develop and scale up hydrogen use in the power sector. Building on recent announcements, **we will engage with industry to understand the economics and system impacts of introducing hydrogen into the power sector, including sector coupling and hydrogen energy storage.** Further updates will be published in due course, including the response to our recently published Decarbonisation Readiness Call for Evidence.

We will review the progress of our recent actions, and engage with relevant stakeholders and hydrogen projects early to ensure there is suitable support for hydrogen in the power sector to deliver against our vision for 2030.

We will also take steps to demonstrate the technologies needed for hydrogen use in power. As detailed in the Chapter 2.3, **subject to competition we are supporting innovation in energy storage through electrolysis via our £68 million Long Duration Storage Competition.** As set out in Chapter 2.4.1 above, **we will also engage with**