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Low-carbon hydrogen supply

Large amounts of hydrogen may be needed as a substitute for fossil fuels in order for the UK to meet its 2050 net zero greenhouse gas emissions target. However, significant challenges remain in scaling up the supply and demand for hydrogen. The Government will publish a Hydrogen Strategy in 2021.

Overview

- Current methods of producing hydrogen emit greenhouse gases. Low-carbon hydrogen production will need to increase in future for the technology to play a significant role in tackling climate change.
- Future levels of hydrogen use are highly uncertain and depend on wider developments in the energy system.
- Hydrogen can be stored at scale for long timeframes, providing energy storage that may help wider sectors reach net zero.
- Hydrogen produced from natural gas with CO_2 capture infrastructure is closer to large-scale use, but it results in residual emissions
- Hydrogen produced using renewable electricity is more costly but could be competitive in the 2030s.

Background

Hydrogen is a gas that is widely used in oil refining and in fertiliser production. Some forms of transport, industry and heating applications, which mainly use petroleum fuels and natural gas at present, may be able to use hydrogen in future in order to reduce emissions.[1,2] Hydrogen does not emit carbon dioxide (CO_2, a greenhouse gas, GHG) when used. Hydrogen could therefore be particularly useful in applications that are otherwise difficult to decarbonise. Independent advisers the Climate Change Committee (CCC), as well as industry and academics, suggest that large amounts of hydrogen will be needed to meet the UK's 2050 net zero GHG target.[3]

However, there is very little pure hydrogen present on Earth and it therefore has to be produced. Most existing large-scale production relies on fossil fuels, resulting in GHG emissions. Newer approaches, which result in few or no emissions, produce what is referred to as 'low-carbon' hydrogen.[4] There are infrastructure, commercial, regulatory and policy challenges to developing and scaling low-carbon hydrogen production.[5,6] These challenges mean that it is not clear whether low-carbon production can be scaled up to meet possible demand, creating uncertainties about the possible extent of hydrogen's role in the UK and globally.

The Department for Business, Energy and Industrial Strategy (BEIS) is expected to publish a Hydrogen Strategy before autumn 2021. Hydrogen strategies have already been published by the European Commission, some EU states, Australia and others.[7–10] This POSTnote summarises methods for producing, transporting and storing hydrogen. It outlines how low-carbon hydrogen supply could develop in the UK, and the challenges in scaling up production to meet future demand. It does not consider potential end-uses of hydrogen.

Hydrogen production processes

Hydrogen must be obtained from water, fossil fuels or organic material (biomass), requiring additional energy to drive a process.[11–13] Specific colours are often used to refer to different hydrogen production processes. The hydrogen molecules produced are the same in each case, but different processes produce differing amounts of impurities and have different carbon footprints.

Fossil- and biomass-based production

Around 95% of current global hydrogen production uses a thermochemical process (Box 1), which splits a fossil fuel or biomass into hydrogen and carbon dioxide (CO_2) using high-temperatures.[6,12,13] All such production currently releases the CO_2 into the atmosphere, contributing to climate change.[6,14] The majority of current production uses natural gas (so-called grey hydrogen).[6] To obtain low-carbon **blue hydrogen**, natural gas is converted into hydrogen (Box 1), and the resulting CO_2 is captured and placed into permanent storage using carbon capture and storage (CCS) infrastructure (CBP8841). CCS comprises a range of technologies that capture

Box 1: Thermochemical production processes
Most thermochemical processes work by 'reforming' a hydrocarbon (splitting it into CO_2 and hydrogen). As well as less developed techniques,[6,12,15–17] main approaches include:

- **Steam methane reforming (SMR)** reforms natural gas using steam with a catalyst, with the gas also burned to provide heat for the reaction.[12] Around half of global hydrogen is produced using SMR. An SMR plant's energy efficiency is typically around 70% (i.e. 70% of the energy in the input is conserved in the hydrogen product).[6,18]
- **Autothermal reforming (ATR)** adds oxygen into partially reformed natural gas to combust some of the hydrogen, providing the heat for further reforming reactions across a catalyst. ATR plants can as efficient or more efficient than SMR.[6,12,18–20]
- **Partial oxidation** is used to reform heavy fuels such as oil and coal. Around a third of global hydrogen production is produced through partial oxidation of oil.[6,12,13]
- **Gasification** converts coal or biomass to a hydrogen-rich syngas, which is processed further to increase the hydrogen content**.** Coal gasification is mature, producing around a fifth of global hydrogen,[13] but is low-efficiency and produces high levels of CO_2. Biomass, such as wood, requires pre-treatment before gasification, substantially increasing the complexity of the process. When combined with CCS, biomass gasification could be used for greenhouse gas removal (PN 618).[6,12,18,21,22]

Box 2: Electrolytic production processes
Three most common electrolytic processes are differentiated by the medium in which water is split (the electrolyte).

- **Alkaline** electrolysers are an established technology used to produce nearly all electrolytic hydrogen today. A relatively constant power supply is required, making them less suited to using variable renewable electricity. Their efficiency is around 70%.[6,12,30]
- **Polymer electrolyte membrane (PEM)** electrolysers use solid plastic electrolytes. They are developing quickly but not yet widely deployed. They are better suited to a range of plant sizes and electricity variability electricity but are made of more expensive materials. The latest PEM system efficiencies are around 75%.[6,12,31]
- **Solid oxide electrolyser cells (SOECs)** use a ceramic material at high temperature. No commercial plants are in operation, but efficiency may be around 74-81%. They have low material costs, but high temperatures may cause the materials to degrade over time.[6,12]

waste CO_2 from industrial or power production processes, before compressing, transporting and storing it underground so that it cannot contribute to climate change. There are two CCS facilities operational in the UK and others worldwide.[23] The technology is mature but has not yet been widely deployed due to high infrastructure costs and commercial barriers.[24]

Electrolytic production
Electrolysis is the process of splitting water into hydrogen and oxygen using electricity (Box 2). If this electricity is generated from renewable energy sources, the result is termed **green hydrogen**, which is low carbon. Nuclear power or the heat it generates could also be used to produce low-carbon electrolytic hydrogen. The principles of electrolytic hydrogen production are long-understood.[25] However, it currently only accounts for around 4% of global production and is typically powered by grid electricity with higher CO_2 emissions. Electrolysers can produce very high-purity hydrogen (>99.99%) which is necessary for use in hydrogen fuel cells.

Biological production
Microorganisms breaking down biomass such as food waste in the absence of oxygen can produce hydrogen, known as 'anaerobic digestion'.[12] This is already widely done to produce biomethane (PN 565) but can be adjusted to increase hydrogen yield. Biological hydrogen is unlikely to contribute significantly to UK supply as it is in early stages of development and there are limited amounts of sustainable biomass available.[26] However, it may produce higher-value chemicals as part of a 'biorefinery' producing a range of biomass products.[12,27–29]

Low-carbon hydrogen supply in the UK
Low-carbon production methods would need to expand substantially if hydrogen is to be used at scale to help reduce global GHG emissions. In the UK, green and blue hydrogen production are the primary low-carbon approaches being considered by government and industry. There is comparatively less policy interest in hydrogen produced with nuclear power in the UK. Academics and other researchers suggest that advanced nuclear technologies could provide hydrogen in future, subject to cost reductions.[32] The UK nuclear industry is exploring hydrogen production,[33] and further interest exists internationally.

Estimates of the carbon footprint of different hydrogen production methods vary widely and depend on 'life-cycle' emissions, from the manufacture of production technology to the way that heat and power for hydrogen production is generated.[6,12] Green hydrogen has the potential to be lowest carbon in the long-term, if sufficient renewable power is available.

Scale of future supply and demand
Although there is agreement that low-carbon hydrogen will have a role in the future energy system, its exact scale is unclear. Energy models illustrate how demand could grow in future, using assumptions around: the level of consumer behaviour change; innovation; cost development; and wider changes in energy, transport and agricultural systems. UK and global models generally suggest lower hydrogen demand in scenarios with greater energy efficiency, electrification and sustainable lifestyle choices (e.g. in diet and travel).[3,34,35]

In 2016, UK hydrogen production was 27 terawatt-hours (TWh, a unit of energy),[13] while total natural gas demand was 896 TWh and electricity consumption was 304 TWh.[36,37] The central scenario in the CCC's 6th Carbon Budget modelling projects 105 TWh of low-carbon hydrogen demand in 2035 and 225 TWh in 2050 (with a range of 160-375 TWh across scenarios).[3] National Grid, which produces scenario models of the future energy system, suggest 152-591 TWh in 2050.[35]

A key issue in increasing hydrogen use is the ability to develop sources of demand (such as industrial heat applications) and low-carbon supply at the same pace.[38] Technical and cost barriers currently exist to developing these at scale. Technological differences between blue and green hydrogen production mean that developing a low-carbon system around them involves long-term systemic decisions on the wider energy

Box 3: The Low-Carbon Hydrogen Supply Competition
A two-phase competition in 2018-2020 provided £33m to develop blue and green hydrogen production. Five UK demonstrator projects received funding in the second phase:

- **Gigastack** aims to develop large-scale green hydrogen production using PEM electrolysers (Box 2).[39,40] 100 MW of electrolysers will initially supply hydrogen to a Humberside refinery before manufacturing is scaled up.
- **HyNet** aims to develop a blue hydrogen production facility in the North West industrial cluster, with the ultimate aim of up to 18 TWh annually (equivalent to 2 GW running at full capacity) by 2030.[41–43]
- **HyPER** aims to construct a 1.5 MW blue hydrogen plant using a novel thermochemical process by 2024.[44]
- **Acorn** is a CCS and blue hydrogen demonstration project in Scotland using North Sea gas infrastructure.[45]
- **Dolphyn** is a green hydrogen production project using floating offshore wind (POSTnote 602) near Aberdeen. It aims to develop a desalination unit with 10 MW PEM (Box 2) electrolyser by 2024, and will pipe hydrogen to shore.[46]

In May 2021, BEIS announced a second round of the competition, which will award £60m by 2024/25.[47]

system.[48–50] Several UK projects are underway to demonstrate low-carbon production (Box 3).

Scaling up blue hydrogen
Blue hydrogen is likely to be produced at fewer, but larger, projects, as the technology benefits from economies of scale and requires CCS networks (which are not yet in place). Efforts to develop blue hydrogen are focused around industrial clusters, close to demand, shared infrastructure and geological storage sites (see *Storing energy using hydrogen*).[19,50–56] In the 2020s, blue hydrogen production is likely to be cheaper and more scalable than green in the UK.[6,18] Earlier blue projects could stimulate demand and help the wider hydrogen industry to scale up before green production becomes competitive.[3]

Residual emissions from blue hydrogen production
Around 80-90% of CO_2 emissions can be captured from a process fitted with current CCS technology.[48,57] Higher capture rates are more achievable with ATR (Box 1) and other novel technologies,[6] but the additional equipment needed to do so would reduce efficiency.[20,53,58,59] In addition, natural gas extraction and transportation results in 'upstream' GHG emissions from leaks, venting and flaring, which is not captured and may occur in or outside of the UK.[60–63] Any remaining emissions from blue hydrogen production in 2050 would need to be offset with greenhouse gas removal (PNs 549 and 618). This is not yet available and will likely also be needed for other difficult-to-decarbonise sectors.[48] Biomass gasification with CCS (Box 1) could provide some of this alongside hydrogen production. Researchers have expressed concerns that blue hydrogen risks 'carbon lock-in' as it shares infrastructure, business models and knowledge with natural gas.[64,65]

Scaling up green hydrogen
The CCC's 6th Carbon Budget central scenario suggests 21% of hydrogen production could be green in 2035, and 44% in 2050.[3] As the cost and efficiency of electrolysers is less dependent on size, green hydrogen can be produced at small or large scale, and may therefore be deployed over a wider geographic range.[48] Multiple electrolysers may also be 'stacked' to form a single larger plant.[31,40] Electrolyser manufacturing will need to increase substantially to meet projections of green hydrogen production. The largest manufacturers currently produce less than 30 megawatts (MW, a unit of power[66]) of electrolyser capacity annually, and most electrolyser units have a capacity of less than 1 MW.[39] The CCC's central scenario suggests that 20-35 gigawatts (GW, 1000 MW) of low-carbon hydrogen production capacity (green or blue) would be needed by 2035.[67] The Gigastack project (Box 3) aims to manufacture 1 GW of electrolyser capacity each year by the mid-2020s.[39,40]

Using wind power for green hydrogen production
UK waters have the technical potential to host more offshore wind power than is required to meet net zero electricity generation.[68] The wind industry advocates using this potential for green hydrogen production.[49,69] Approaches include:[39]

- Connecting an electrolyser to the grid, with a commercial contract to purchase electricity from a distant wind farm;
- Directly connecting an electrolyser to a wind farm, which either powers the grid or, when electricity demand is low, diverts the electricity to produce hydrogen;
- Directly connecting an electrolyser to a wind farm (on or offshore), which solely powers hydrogen production that is piped or shipped to a hydrogen transportation network.[70]

Green hydrogen production may be useful for balancing the variability of wind power.[71] The CCC suggests that by 2050, 65-140 GW of offshore wind capacity could be needed for electricity.[72] When electricity demand is low and renewable output is high (e.g. when it is windy), surplus electricity that would otherwise be curtailed (purposefully reduced to avoid damaging the network) could be used to produce green hydrogen. If using surplus electricity, plants may not be fully utilised throughout the year and efficiency may reduce, though the electricity price would be lower for the producer.

Transporting and storing hydrogen
Hydrogen can be transported to geographically disperse end-users, who may be concentrated in specific locations (e.g. industrial clusters) or more widespread (e.g. to supply domestic heat). The most cost-effective method of transporting large volumes of hydrogen gas is via pipeline. It can also be compressed or cooled to a liquid (at around -250°C) and transported by road, rail or ship, but this adds additional costs and energy losses. Before shipping, it can be converted to ammonia, which has a well-established global transportation infrastructure, and can itself be used as a fuel for shipping.[6]

The gas network and hydrogen
While new hydrogen pipelines could be constructed, it may be possible to repurpose parts of the existing natural gas network to transport hydrogen at lower cost. Many in the heating sector advocate this as a way of using hydrogen to decarbonise domestic heat (PN 565).[73] An initial blend of up to 20% hydrogen may be possible with low disruption to domestic consumers,[74] and could provide up to 7% CO_2 savings and an early market for producers.[75] Alternatively, it may be possible to carry 100% hydrogen in parts of the network, requiring home appliance conversion and wider infrastructure upgrades. Each user on that part of the network would need 'dual-fuel' systems such as hydrogen-ready boilers. There is uncertainty around the

feasibility of network conversion, the extent of a future hydrogen network's size, and relative costs compared to other decarbonisation options. The GB gas network has two parts:

- **The National Transmission System (NTS)** transports gas through steel pipes at high pressure to large industrial users and local gas systems. It is operated by National Grid.
- **The Gas Distribution Networks (GDNs)** supply gas at lower pressure to the majority of users. A programme to upgrade the GDNs' iron pipework to polyethylene is due to finish in 2032. There are eight operators across GB.

The GDN's polyethylene pipes can transport unblended hydrogen.[48,76] A National Grid research project aims to assess whether the NTS can be repurposed to transport hydrogen.[77] The NTS was previously considered unsuitable for unblended hydrogen due to concerns it may make steel pipes brittle.[78] However, emerging evidence suggests that this may be less of an issue or that remedial measures can be put in place.[79]

Using hydrogen to store energy

Hydrogen could be used to store energy to help meet variations in energy demand between summer and winter, and for extended periods of low renewable output.[80] Electricity storage, such as large grid-connected batteries, may be less suited for long-term, large-capacity storage. Researchers estimate that around 100-150 TWh of hydrogen storage capacity would be needed to meet seasonal variation if all current natural gas demand was met with hydrogen (a maximum case).[53,81–83] Hydrogen is three times less energy dense than natural gas so larger volumes are needed for an equivalent amount of storage. Several options exist:[84]

- **Salt caverns** have been used in the UK for many years to store hydrogen underground.[85] Many exist, but the largest could only store around 1 TWh; most are much smaller.[86,87]
- **Depleted oil and gas fields** and porous rock may be able to store CO_2 or hydrogen,[88] and are larger than salt caverns: North Sea gas fields have an estimated storage capacity of 10-1000 TWh.[81,82] Feasibility research is underway.[89,90]
- **Linepack** refers to gas stored within higher pressure pipes on the network.[91] Depending on the level of network conversion, it could store a smaller amount of energy.

Commercial and regulatory challenges

Costs of producing low-carbon hydrogen

Cost estimates of future low-carbon production are highly uncertain.[12] The overall cost of supply (and hence consumer costs) include capital (construction and financing); operational (fuel costs such as natural gas, or electricity); transportation; and storage. Operational costs are typically the largest component, and are sensitive to the technology's efficiency and, for blue, changes in gas prices.[6] As with any new decarbonisation technology, it will entail significant infrastructure change and additional costs compared to the current method (e.g. natural gas).

Blue hydrogen is the most cost-effective production option in the near-term,[6,18] but as more UK wind is installed, green hydrogen plants will be able to access lower-cost electricity from surplus generation.[48,72] Electrolyser costs are also expected to reduce as deployment increases.[71] As a result, the costs of large-scale UK green hydrogen production could become lower than blue in the 2030s.[49,92,93] Electricity cost reductions will also make electrification of some end-uses cheaper, increasing the competition that hydrogen faces.

Government support for hydrogen production

As with any new technology, government can help to overcome risks for early private investors, and to coordinate supply and demand, to develop a market.[94] BEIS oversees policy for hydrogen production and administers several funds to support demonstration. It is expected to publish a Hydrogen Strategy before autumn 2021, setting out its approach to supporting future investment, business models and regulation.

Government investment and deployment targets

To date BEIS has funded a £33m Low-Carbon Hydrogen Supply Competition (Box 3) for demonstrator plants,[95] and blue hydrogen demonstration projects have also received funding under BEIS' CCUS Innovation Programme.[42] A £240m Net Zero Hydrogen Fund announced in November 2020 will aim to support 5 GW of low-carbon production by 2030,[96] though industry stakeholders suggest that this target is low.[97–99] The Scottish Government has its own target of 5 GW by 2030.[100]

Hydrogen business models

The UK Government is expected to outline a business model in 2021 that sets out the commercial framework for producing and selling low-carbon hydrogen.[51] A 2020 BEIS-commissioned report suggested that a future business model should address cost differences between hydrogen and fossil fuels, encourage use in the most valuable applications, and initially support less mature production (i.e. green).[38] It suggested using a Contract for Difference (CfD) scheme to support production projects over 100 MW.[38] CfDs are currently used to support low-carbon power generation, by ensuring producers are paid a fixed price for the electricity they produce, for multiple decades.[96,101] BEIS will consult on hydrogen business models in 2021.[51]

Regulating hydrogen

Common standards that define acceptable thresholds for purity, carbon footprint and safety are needed to allow for exports and use across applications. There is currently no legal definition of low-carbon hydrogen,[102,103] and BEIS is expected to outline a standards consultation as part of the Hydrogen Strategy. As with natural gas, safety considerations exist when transporting, storing and using hydrogen (PN 565). The Health & Safety Executive (HSE) is responsible for the regulatory framework for hydrogen. BEIS and HSE are working with trial projects to examine future regulatory codes and standards.[74,104–109]

Global hydrogen markets

There is global interest in using low-carbon hydrogen.[110] Many sunny or resource-rich states (where production is cheaper) have begun or are interested in exporting, such as Australia, Chile and Norway. Saudi Arabia has begun exporting hydrogen-derived ammonia.[10,110,111] The majority of future UK supply is likely to be domestic, but a proportion may be imported (the CCC suggests 13% in 2050).[72] UK hydrogen export potential is low in most scenarios, as cheaper sources are likely to exist abroad.[3,112] The Scottish Government is exploring the potential for hydrogen export.[113] There are UK export opportunities for skills and technology such as electrolysers.[39,114]

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