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The role of hydrogen in a net zero energy system

Executive summary

Hydrogen is a highly versatile *energy vector* that could be used in many hard-to-decarbonise sectors where other energy vectors, such as electricity, may not be suitable – for example, in certain industrial direct-firing processes. This is because hydrogen has a high *specific energy* (energy per unit mass), such that, when it is burned, very high temperatures can be readily achieved and it can be stored in large quantities. As such, hydrogen has a valuable and essential role in the net zero transition by providing flexibility across the energy system. However, as the successful scaling up of low-carbon hydrogen production and end uses poses many challenges and is dependent on decisions made in other parts of the energy system, a pragmatic and carefully managed delivery is vital in order to achieve emission reductions and reap the benefits that hydrogen can provide. This report provides an overview of the following areas:

- hydrogen's value as an energy vector
- potential roles of hydrogen in a net zero energy system
- low-carbon hydrogen production methods and the associated risks and dependencies
- policy recommendations for the government to ensure that the benefits of hydrogen for a net zero energy system are realised.

Hydrogen is a chemical element found in many chemical compounds such as water and methane. Generating hydrogen from these compounds requires the input of a large amount of energy, making efficient and low-carbon production of hydrogen a key challenge. The production methods of *grey*, *blue*, and *green hydrogen* are described in Figure E.1. Currently, more than 96% of the UK's hydrogen production capacity produces *grey hydrogen*, which is carbon intensive and not aligned with achieving net zero. While there are multiple hydrogen production methods, which differ by the production process and the feedstock used, this report focuses on the two low-carbon hydrogen production methods predicted to be the most prevalent: 'blue' and 'green' hydrogen production.

There is a significant gap between current levels of low-carbon hydrogen production and the projected levels needed to meet the UK's carbon budgets and achieve the target of net zero emissions by 2050. To succeed, the government's commitment to hydrogen will require rapid development of a new low-carbon hydrogen production capacity, which is essentially starting from scratch.

Note: Terms in *italics* are defined in the Glossary on Page 34.

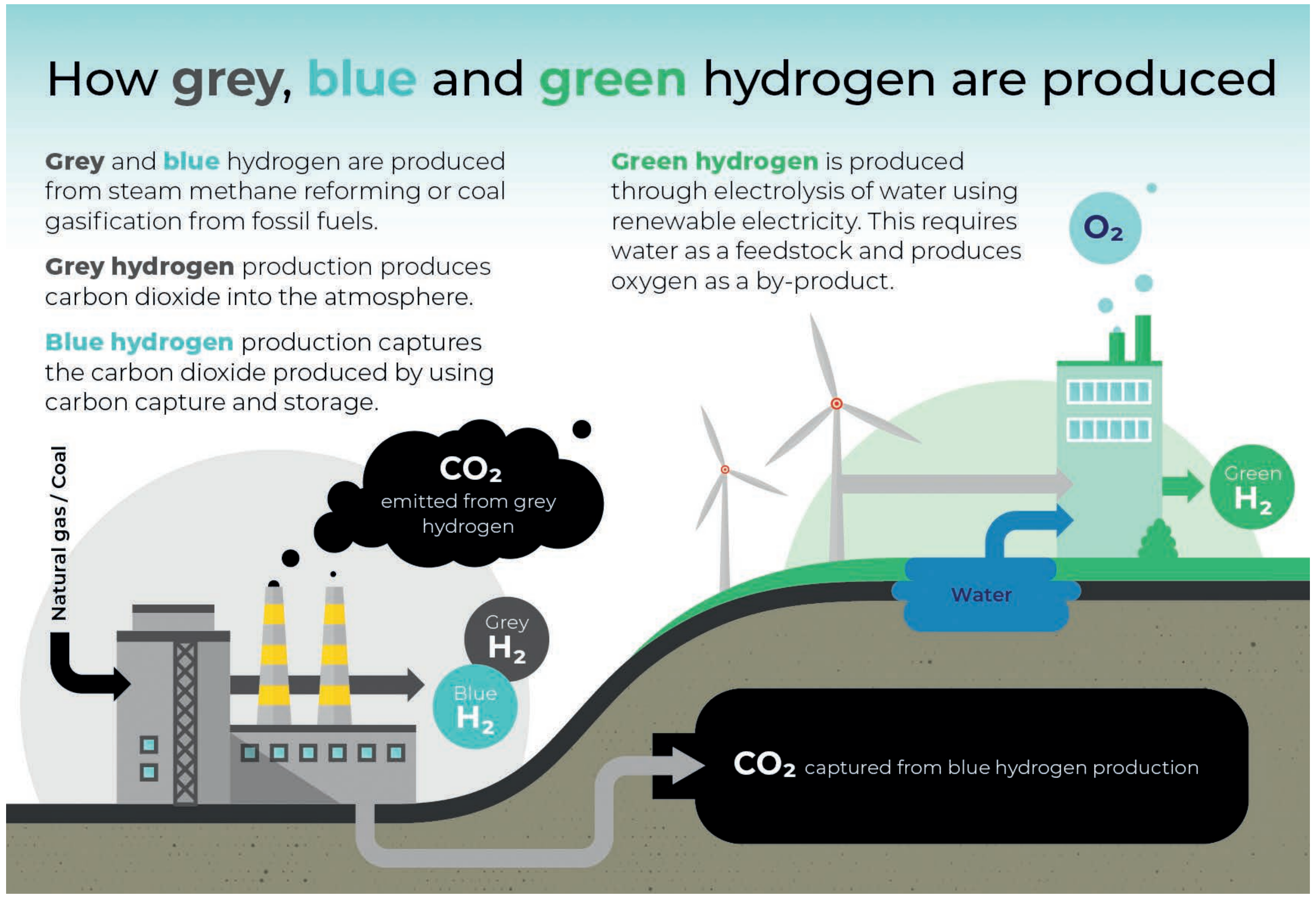


Figure E.1. | Grey, blue, and green hydrogen production methods

While hydrogen has significant potential in certain sectors to become the best or only decarbonisation option available, scaling up low-carbon hydrogen production in such a short time frame bears many risks and dependencies. It is vital to recognise and manage these risks and dependencies during the process of scaling up hydrogen's role in the energy system to deliver rapid emissions reduction and maximise the whole-system benefits that are achievable. Risks inherent within all of these areas must be managed if hydrogen production and end use are to be low carbon and therefore contribute to achieving net zero.

This report outlines in detail the most critical issues related to the scaling up and integration of *blue* and *green hydrogen* into the wider energy system. These are as follows:

Blue hydrogen

- dependence on *carbon capture and storage technology*
- dependence on fossil fuel supply
- *fugitive emissions* from fossil fuel extraction and blue hydrogen production and transportation processes

Green hydrogen

- dependence on renewable electricity generation and supply
- competition for renewable energy between direct electrification and green hydrogen production
- *electrolyser* build rates and supply of the critical scarce materials required

Wider hydrogen value chain

- blue and green hydrogen competition
- 'chicken-and-egg' situation in the simultaneous scaling up of production and end use and the complexity of the hydrogen value chain
- skills gap
- safety and public trust
- global production and use of hydrogen
- cost and emissions uncertainties of hydrogen imports.

Risks inherent within all these areas must be managed if hydrogen production and end use are to be low carbon and therefore contribute to achieving net zero. A technology-neutral and outcome-oriented approach is essential to ensure low-carbon hydrogen value chains develop in practice. The government has rightly recognised this need by developing a low-carbon hydrogen standard that focuses on the greenhouse gas intensity per heating value of hydrogen.

The possible end uses of low-carbon hydrogen were reviewed to understand its potential roles in the future energy system, the benefits for decarbonisation, and the risks and uncertainties to be addressed. This includes current uses of hydrogen, which, importantly, will also need to be decarbonised alongside the scaling up of low-carbon hydrogen production and its end use in areas of the energy system in which it currently does not play a role. The potential roles of low-carbon hydrogen in a net zero energy system encompass:

- **industry** – chemical feedstock for industrial process, primary steelmaking, and industrial heating
- **power** – medium- to long-term energy storage, dispatchable low-carbon electricity generation, and whole-system flexibility
- **transport** – aviation, shipping, heavy goods vehicles and public service vehicles, rail and off-road vehicles (either as hydrogen or as an input to synthetic fuels)
- **heat and buildings** – domestic heating and gas grid blending (see also Section 2).

The best use of low-carbon hydrogen has yet to be determined, but it is likely to be a combination of where its deployment is either the best or the only low- or zero-carbon option available and where it can achieve the highest carbon savings and cost efficiencies from a whole-system perspective. Those possible end uses should be supported by investment in rapid and early pilot projects to prove feasibility, address outstanding uncertainties, and drive down costs to enable the transition and support industry adoption.

When scaling up the role of hydrogen in the energy system, the strategy chosen will have implications for the ultimate end uses in which hydrogen will play a role. Given that the availability of low-carbon hydrogen will be limited while production capacity is being scaled up, there is a need to ensure the best use of hydrogen from the point of decarbonisation of the energy system as a whole.

A strategy that maximises the production of low-carbon hydrogen while also managing the risks will require a region-specific approach to developing local hydrogen economies. Low-carbon hydrogen production and end use should focus on industrial clusters where current production and use of *grey hydrogen* is located. When low-carbon production capacity (and the enabling infrastructure this requires) has been sufficiently scaled up in these clusters, hydrogen deployment can be expanded from these industrial clusters for more widespread use in the energy system. This means that the degree of hydrogen deployment will vary significantly across different regions and be subject to regional variations such as the cost and efficiencies of low-carbon hydrogen production, storage and transportation infrastructures, the availability of low-carbon hydrogen over time, and the development of other decarbonisation options for different end uses.

Hydrogen is likely to become the most effective or the only decarbonisation option for some end uses. Therefore, it will play a critical role in any net zero energy system. To capture the opportunities presented by low-carbon hydrogen and make the best use of its potential to contribute to achieving net zero, policies must:

1. **achieve a rapid scaling up of low-carbon hydrogen infrastructure – with particular attention to those end uses for which hydrogen deployment offers the greatest value to decarbonisation of the whole energy system**
2. **manage the risks and dependencies when scaling up hydrogen value chains.**

These two overarching requirements need to be achieved in the next few years if low-carbon hydrogen is to be successfully scaled up as part of a net zero energy system. This report further breaks these down into a set of more detailed policy recommendations that are prioritised in terms of which actions need to be taken now and which next (within the next five years) (see Section 4, Tables 4.1 and 4.2).

Contents

Introduction: **Scope of this report**

Hydrogen can carry energy to many hard-to-decarbonise sectors with no greenhouse gas emissions at the point of use, giving hydrogen a valuable role in a net zero energy system. However, as the successful scaling up of low-carbon hydrogen production and end uses poses many challenges and is dependent on decisions made in other parts of the energy system, a pragmatic and carefully managed delivery is vital to achieve emission reductions and reap the benefits that hydrogen can provide. This report provides an overview of the following areas for consideration:

- hydrogen's value as an energy vector
- potential roles of hydrogen in a net zero energy system
- low-carbon hydrogen production methods and the associated risks and dependencies
- policy recommendations for the government to ensure that the benefits of hydrogen for a net zero energy system are realised.

Section 1: **Hydrogen's value as an energy vector**

Hydrogen is highly reactive and is bonded in many chemical compounds such as water and *methane*. Producing it from these compounds requires a large amount of energy input, making efficient and low-carbon extraction of hydrogen one of the main challenges in hydrogen production.

Hydrogen can be used as an *energy vector* (ie it can be produced, transported, and stored as a means of delivering and/or storing energy) in many hard-to-decarbonise sectors, where other energy vectors such as electricity are not suitable – for example, due to energy density requirements, availability and capacity of electricity infrastructure, or other technical requirements. This is because hydrogen can be stored in large quantities and because it has high *specific energy*, such that, when it is burned in industrial heating processes, for example, very high temperatures can be readily achieved with water as the end product.

In view of hydrogen's potentially valuable future role, it has been receiving a great deal of attention from government and industry, both in the UK and globally. The UK government has set out high expectations for the role of hydrogen and is currently aiming for 10 gigawatts (GW) or 84 terawatt-hours (TWh)[1] of low-carbon hydrogen production capacity by 2030,[2] and is estimating demand of between 250 and 460 TWh in 2050.[3] This is equivalent to 20–35% of the UK's total expected energy consumption in 2050.[4] To put this into context, the UK currently produces around 27 TWh of hydrogen each year, 96% of which is *grey hydrogen* and is used predominantly as industrial feedstocks in the petrochemical and fertiliser sector.[5] The process of grey hydrogen production produces carbon dioxide (CO_2) and is incompatible with net zero.[6]

There are significant gaps between current levels of hydrogen production and use and those anticipated as a requirement for achieving net zero by 2050. The predicted demand of between 250 TWh and 460 TWh in 2050 represents an uplift in the magnitude of between nine to 17 times the current *grey hydrogen* production capacity. Furthermore, production of hydrogen would need to shift away from grey hydrogen to near zero-carbon forms of production, which will entail increased demands for key requisite technologies such as *carbon capture and storage* (CCS), for *blue hydrogen*, and renewable electricity generation and *electrolysers*, for *green hydrogen*.

To succeed, the government's commitment to hydrogen will require rapid development of a new low-carbon hydrogen production capacity, which is essentially starting from scratch. Innovation must be backed by policies and funding for technology development. Infrastructure must be built to produce, store, and transport hydrogen safely and reliably without significant losses due to leakage, regulated by an ambitious low-carbon standard, and end uses will need to be technologically enabled to use hydrogen – all in a short time frame.

As hydrogen is the lightest element and very reactive, it could be challenging to store and transport for certain practical uses. These are areas in which ammonia, a hydrogen-derived *energy vector*, could play a role, as ammonia is more stable and can be stored and transported at much higher energy density by volume than hydrogen. It also has a potential role in decarbonising shipping[7] (see Section 2 for more details). However, ammonia is more toxic and corrosive than hydrogen. Currently, about 43% of pure hydrogen produced globally is used as an input for ammonia synthesis.[8] The most common uses of ammonia are for the production of fertiliser, plastics, and other products, and as a refrigerant. The Discussion Box presents some key considerations for ammonia production and use.

Discussion box: Ammonia – carbon, health, and environmental considerations

The key role of ammonia today is as the feedstock for inorganic fertilisers, which support food production for around half of the world's population. It is predominantly produced via the *Haber–Bosch process*, a catalytic reaction of hydrogen and nitrogen at high temperature and pressure.[9]

Carbon intensive production: Ammonia production is the largest CO_2-emitting industrial chemical process, accounting for around 2% of the annual greenhouse gas emissions globally.[10] The production involves two processes: (1) *steam methane reforming* and (2) the Haber–Bosch process. Both processes consume fossil fuels, such as natural gas and coal, as energy input and as feedstocks to produce hydrogen from steam methane reforming.[11] Decarbonisation of ammonia production is under development with options such as applying *CCS* to the existing manufacturing process and using renewable electricity for *electrolysis* to produce *green hydrogen* and energy input for the Haber–Bosch process.[12]

Health concerns: Ammonia is corrosive and potentially toxic. Its risk levels increase with increasing vapour pressure. However, ammonia is readily detectable by smell at concentrations substantially below levels that cause any lasting health consequences.[13]

Environmental impacts: The transport, storage, and use of ammonia in the energy system could cause non-climate-related environmental impacts. Leakages of ammonia into the environment would disrupt the nitrogen cycle and lead to production of nitrogen oxides. The environmental concerns associated with nitrogen oxides include biodiversity losses, eutrophication, air-quality issues such as particulate matter and formation of smog, greenhouse gases emissions, and stratospheric ozone loss.[14]

Section 2: **Potential roles of hydrogen in a net zero energy system**

According to the *Climate Change Committee* (CCC) *Sixth Carbon Budget*'s recommended 'Balanced Net Zero Pathway' scenario,[15] to achieve net zero by 2050, hydrogen use would be comparable in scale to today's electricity use – around 350 TWh a year.[16] The CCC also emphasised that hydrogen use should be restricted to areas less suited to electrification specifically, shipping, parts of industry involving high-temperature processes, and as an energy storage mechanism that provides flexibility to the power system.[17]

The size of the challenge involved in scaling up low-carbon hydrogen production is significant. As the *CCC* has indicated, the best value from hydrogen for decarbonisation is likely to come from end uses in which hydrogen is either the most energy- and cost-efficient decarbonisation option or is the only option available.[18] Section 2 of the present report reviews the possible end uses of low-carbon hydrogen to understand its potential roles, the benefits for decarbonisation, and the risks and uncertainties still to be addressed. This includes current uses of hydrogen, which, importantly, will also need to be decarbonised alongside the scaling up of low-carbon hydrogen production and its end use in areas of the energy system where it currently does not play a role.

Industry

The UK government's industrial decarbonisation strategy has analysed the emissions abatement of deep decarbonisation technologies – technologies that enable full decarbonisation, including *CCS*, *bioenergy with carbon capture and storage* (BECCS), electrification, and hydrogen – across different scenarios. It sees hydrogen playing a prominent role in industrial decarbonisation, contributing 25 – 51% of total abatement among the deep decarbonisation technologies, with total hydrogen use in industry ranging between 28 and 86 TWh, abating 7 to 18 million tonnes of carbon dioxide ($MtCO_2$) a year across different scenarios by 2050.[19] This is largely in line with the *CCC's Sixth Carbon Budget* – recommended Balanced Net Zero Pathway scenario's estimates of a 66 TWh hydrogen demand, and abating 14 $MtCO_2$ a year in 2050.[20]

Chemical feedstock for industrial processes: The current major uses of hydrogen are for *petroleum refining*, *fertiliser production*, methanol production, and various other industrial processes.[21] For petroleum refining, hydrogen is used in *desulphurisation* and *hydrocracking* to break down heavy residual oil into more useful hydrocarbons, but this demand is expected to decline in the long term as the oil demand falls. For fertiliser production, hydrogen is an essential input for the *Haber–Bosch process* to produce ammonia. Of the global ammonia produced in this way, 80% is for agricultural fertilisers.[22] Methanol is produced for use in a range of products such as paints, plastics, and explosives. The hydrogen demand for methanol production will likely increase as plastic production shifts away from fossil fuel-based production processes.[23]

Primary steelmaking: Hydrogen could play an important role in decarbonising steel production. The currently implemented alternative options for lowering the carbon intensity of steel production, such as making efficiency improvements, recycling, and *CCS* to capture the emissions from burning fossil fuels, can only achieve partial emission reduction. In the primary steelmaking process known as the 'direct reduction of iron', hydrogen can substitute fossil fuels as the sole reducing agent to produce *direct reduced iron* (DRI) and water instead of CO_2 as a by-product. In the next stage, DRI is then converted to steel using an *electric arc furnace* (EAF), the alternative to *basic oxygen furnaces* in this stage. DRI–EAF is an alternative primary steelmaking process to the traditional coke-fired *blast furnace* and *basic oxygen furnace* process and has the potential to achieve full decarbonisation.[24]

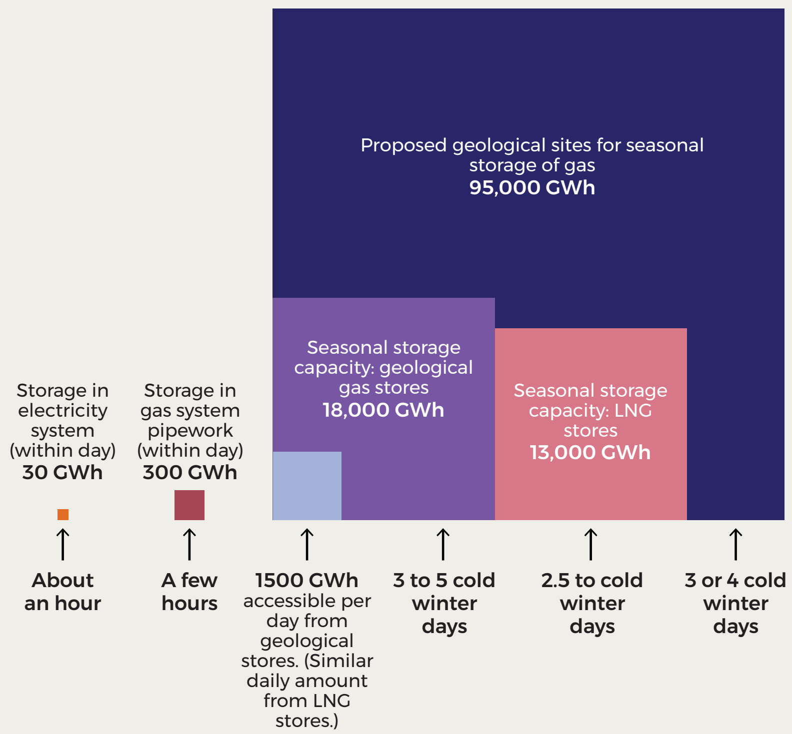
Industrial heating: Hydrogen is likely to be the only option available to substitute fossil fuels in certain industrial direct-firing processes (such as furnaces and kilns) where the combustion gases come into direct contact with the product that is being heated. Biomass and electrification are less technically suited for this as they could only achieve partial substitution due to the high temperature requirements (up to 2000°C).[25] In addition, hydrogen could be the most cost-effective fuel switching option for much of the fossil fuel use in manufacturing based on fuel cost projections. This includes fuel switching for all the main industrial fuel consuming processes, steam production, high- and low-temperature heating (both direct and indirect heating), and reduction processes.[26]

Power

As more of our energy system is electrified, and more of this demand is met with low-carbon renewables that are variable in their output, the need for flexible technologies such as energy storage and demand-side response will grow proportionally. At points of low electricity demand, low-carbon electricity could be used to produce *green hydrogen* as a means of energy storage. This could improve grid resilience by providing an important *system balancing* function, as well as improving energy security by diversifying the sources of power generation.[27] Green hydrogen could play a strategic role in meeting these future power system needs by providing medium- to long-term energy storage, dispatchable low-carbon electricity generation, and whole-system flexibility.

Medium- to long-term energy storage: While hydrogen could be stored in a similar manner to existing storage of natural gas, it is much more challenging than storing other gases due to its small molecular size and explosive nature. Therefore, substantial storage of hydrogen requires purpose-built storage with rigorous safety standards. It must be compressed or liquefied and then stored in geological sites such as underground salt caverns and spent oil and gas wells.[28] Current storage efficiency ranges between 85% and 98% and depends significantly on the compression ratios.[29] A substantial amount of hydrogen could be stored in 95,000 gigawatt-hours (GWh) of proposed geological sites in a similar manner to existing seasonal storage of fossil gas (see Figure 2.1). But the exact demand for hydrogen storage depends on a number of factors such as the storage capacity required for sufficient energy security, the extent of hydrogen deployment, and the cost and development of other energy storage technologies.[30]

Dispatchable low-carbon electricity generation: Conventional *gas turbines* have been optimised for fossil fuels, with larger gas turbines run on natural gas and smaller ones run on oil. Natural gas has been the main fuel for dispatchable generation. Compared with natural gas, hydrogen



Note: LNG = liquefied natural gas

Figure 2.1. | Current energy storage in GB mains gas and electricity systems[31]

molecules are smaller with lower energy density by volume, but hydrogen is more reactive and burns with a higher flame temperature. Existing and new gas turbines can be re-engineered to run on hydrogen with similar efficiencies as burning natural gas, and without a significant increase in capital expenditures in some cases.[32] Trials with hydrogen in various sizes of gas turbines are ongoing and manufacturers of gas turbines are committed to making 100% hydrogen fuel equipment by 2030.[33] The government is also consulting on a decarbonisation readiness requirement for all new gas turbines from 2023.[34] Hydrogen could also be converted into electricity via *hydrogen fuel cells*. Hence, hydrogen could play a role in phasing out unabated gas generation and contribute to achieving the government's target of a fully decarbonised electricity system by 2035.[35] The *CCC's Sixth Carbon Budget* – recommended scenario the Balanced Net Zero Pathway estimates that hydrogen electricity generation could contribute 55% (21 TWh) of the required dispatchable generation (38 TWh) in 2035, with the remaining provided by natural gas with *CCS*.[36] The use of hydrogen – in particular, *green hydrogen* – for electricity generation can improve energy security by reducing the demand for natural gas, and also reduce the demand for CCS.

Whole-system flexibility: Development of hydrogen end uses and associated infrastructure could have emissions and cost benefits by enhancing the flexibility of the whole energy system. Effective coordination between hydrogen and electricity systems enables hydrogen to be produced using *excess electricity* and utilised for various local end uses as a priority or stored for power generation when needed. Some studies have suggested using hydrogen to achieve whole-system optimisation could bring cost reduction in network and generation investment and improve the whole system's flexibility.[37] In terms of technical feasibility and cost, although *electrolysers* are flexible enough to follow fluctuations from wind and solar electricity generation, the cost of electrolysers and renewable electricity remains a barrier for market penetration. However, cost reductions should be achievable over time; for example, the International Renewable Energy Agency (IRENA) have suggested that a combination of cost reductions in renewable electricity and electrolysers and increases in the efficiency and operating lifetime of electrolysers could deliver as much as an 80% cost reduction on the current production cost for *green hydrogen*.[38]

Transport

As the UK government recognised in its transport decarbonisation plan, hydrogen or hydrogen-based fuels are likely to be the most suitable and efficient low-carbon energy source for some forms of transport compared to batteries, due to factors such as energy density requirements, weight and volume restrictions, and refuelling times.[39] From a whole-system perspective, a modal shift in behaviour, resulting in demand reduction, must also be achieved alongside fuel switching to meet the UK's carbon budgets.

Aviation: Alongside the need to encourage a modal shift to more energy-efficient surface transport and an overall demand reduction in aviation, hydrogen could make a significant contribution in decarbonising the aviation sector. For commuter and regional aircrafts, battery electricity may compete with *hydrogen fuel cells* and *sustainable aviation fuels* (SAF) by providing higher torque and quieter operation. For short- to long-haul aircraft, the majority are likely to be decarbonised by SAF, which are partly based on hydrogen, and potentially on direct hydrogen propulsion.[40] Findings from an EU-commissioned study suggested that, in an efficient decarbonisation scenario, 40% of all aircraft will be powered by hydrogen by 2050 and the remaining will be powered by SAF.[41] In terms of non-CO_2 impacts of aviation, SAF would burn cleaner than fossil jet fuel, and produce fewer oxides of nitrogen and less particulate matter. Battery electricity and hydrogen fuel cells do not involve combustion and therefore would not produce any of these pollutants. The lack of soot particles, around which water vapour would otherwise form, may also lead to the formation of thinner contrails, resulting in less severe warming effects.[42] These findings, however, will require further validation in practice.

Shipping: Low-carbon fuels are expected to be the major source of abatement for shipping along with other measures such as improved efficiency and electrification.[43] Hydrogen-derived fuels such as ammonia are likely to be the most widely adopted option to decarbonise the maritime sector, due to the possibility to retrofit ship engines and their higher energy density compared to both hydrogen and battery electricity.[44] Research underpinning the Department for Transport and the Maritime and Coastguard Agency's Clean Maritime Plan has found that the UK has the strongest competitive advantage in hydrogen and ammonia production technologies across all of the decarbonisation options.[45]

Heavy goods vehicles (HGVs) and public service vehicles (PSVs): Hydrogen *fuel cell electric vehicles* (FCEVs) directly compete with *battery electric vehicles* (BEVs) in road transport in terms of total cost of ownership,[46] range, and charging or refuelling times. For cars and vans, the higher efficiency of BEVs compared to FCEVs (86% vs. 41 – 44%)[47] has led to the increased uptake of battery electric cars and vans. This is driving battery technology development, leading to substantial falls in battery prices, as well as improvements in battery energy density and charging times. Such development has increased the range and vehicle sizes in relation to which BEVs can compete with hydrogen FCEVs. For HGVs and PSVs, hydrogen FCEVs may play a role in certain circumstances, such as for business models and routes that are not feasible for overnight depot charging, for locations where high-capacity charging points are not available, and for energy-demanding applications such as those involving high loads or refrigeration.[48] However, to decarbonise the transport sector cost effectively, a modal shift must be prioritised to facilitate the use of the most energy efficient modes for each transport requirement, with measures such as shifting the demand for long-distance HGVs toward electric freight trains.

Rail: Hydrogen trains (including hybrid trains) may play a role in rural rail connections for low-speed passenger services that are currently diesel powered and where overhead electrification is too expensive due to low utilisation. On-train hydrogen storage limitations remain the main barrier, though, for wider hydrogen train applications that have a higher energy demand such as higher speeds, heavier train loads, and longer ranges.[49]

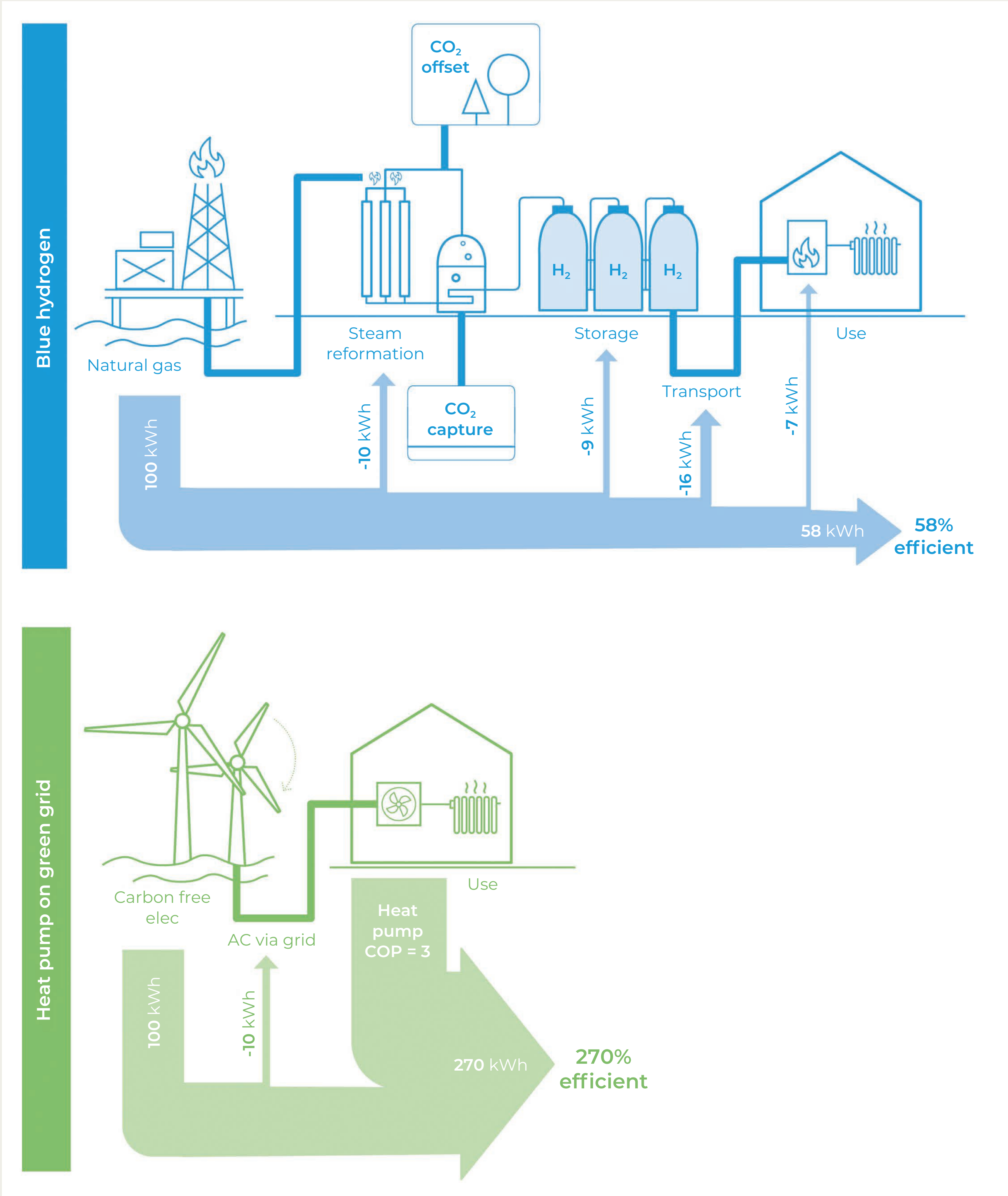
Off-road vehicles: Vehicles such as graders, cranes, construction and mining machinery, and forestry and agricultural vehicles often operate in environments without sufficient grid connections to make electrification feasible. By retrofitting internal combustion engines to burn hydrogen, hydrogen could act as a solution, benefiting from the retention of the existing supply chains and vehicle designs and the elimination of the cooling required by *FCEVs*.[50]

Heat and buildings

Domestic heating: To successfully decarbonise heating, a portfolio of measures is required, including energy efficiency improvements and the deployment of a range of low-carbon heating solutions appropriate for local variations. Hydrogen boilers are among the range of low-carbon heating solutions, along with district heating, heat pumps (including hybrids), and direct electric heating. Hydrogen-ready boilers have the potential to act as a 'drop-in' solution for natural gas boilers, which account for more than 83% of current heating demand.[51] However, there are several factors for consideration when determining the extent and location of each low-carbon heating solution and whether it could reliably contribute to achieving net zero. Therefore, this section is in a different structure to that of the other end uses above, with a number of factors considered (below) to determine hydrogen's potential contribution to decarbonise domestic heating.

i. **Efficiency**: Hydrogen boilers are less efficient than heat pumps due to the losses in the various processes between hydrogen production, transportation, and combustion at the boiler. Owing to the nature of a heat pump's operation (operating similar to a fridge, in reverse, by absorbing heat from air or ground sources), it is the most efficient type of low-carbon heating solution. The useable heat output compared with energy sourced for input of hydrogen boilers using *blue hydrogen* and heat pumps are illustrated in Figure 2.2.

ii. **Building type**: Heat pumps are the most efficient type of low-carbon heating solution, but the application of heat pumps is subject to constraints relating to variations in building type and heat demand, where hydrogen boilers may play a role. The government-funded Electrification of Heat project has successfully demonstrated that the full range of heat pump system types[53] can be installed in a complete range of targeted property types and ages, covering detached, semi-detached, mid- and end-terrace, and flats, from pre-1919 to 2001 and newer.[54] But the project has not demonstrated that the level of operating costs and the amount of disruption during installation would be reasonable to the homeowners. Moreover, a study for the *CCC* on 'hard-to-decarbonise' homes considered that 50% of all types of houses and flats with heritage status[55] are unlikely to be suitable for heat pumps.[56] Also, space-constrained homes[57] are unlikely to be able to accommodate heat pumps that require hot water cylinders, yet 50% of those homes could be suitable for heat pumps with small heat batteries.[58] The efficiency of heat pumps can be compromised if the average room heat loss rate is high (>150 W/m^2), which may result in the required electrical demand exceeding the fuse limit of a typical building.[59] Therefore, hydrogen boilers could play a role in homes where heat pumps are not suitable and that have existing gas grid connections – although zero-carbon district heating may also be part of the solution for these types of homes.



Note: COP = coefficient of performance

Figure 2.2. | Useable heat output compared with energy sourced for input of hydrogen boilers and heat pumps[52]

iii. **Proximity to industrial clusters**: 42% of the demand for domestic natural gas in 2019 was within the six major industrial regions in the UK. Many of these regions are producing *grey hydrogen*, with the potential to transition to *blue* and *green hydrogen* production.[60] The proximity to industrial complexes in these potential low-carbon hydrogen production localities is likely to influence the feasibility (in technical, economic, and carbon terms) of using hydrogen boilers for heating within adjacent buildings, provided gas grid connections can be made secure against safety issues such as hydrogen leakage.

iv. **Safety**: Hydrogen is a highly explosive molecule. It poses many health and safety challenges that must be resolved before approving its widespread use. According to the Hy4Heat safety assessment conducted on behalf of the government and covering detached, semi-detached, and terraced houses, using hydrogen in homes could be up to four times more dangerous than natural gas, but risk can be reduced to a similar level as natural gas by installing two excess flow valves in a property. This assessment therefore concluded that, with this measure and for the properties covered, use of 100% hydrogen could be made as safe as natural gas.[61] Nevertheless, there are limitations of the Hy4Heat assessment that future projects and demonstrations will need to address, such as flats and multi-occupancy buildings, housing that lacks natural ventilation, and the safety of supply through gas networks to homes.[62] The Health and Safety Executive independently reviewed the evidence and was satisfied that the assessment provides an adequate basis for gas network operators to design and risk assess future hydrogen trials.[63]

v. **Consumer choice**: More than 29 million homes will require policy interventions to achieve net zero, and those interventions will vary across different homes.[64] Consumers will want to retain control to choose a heating system that is suitable for their personal needs and lifestyle. If low-carbon heat options are made mandatory, consumers will expect the government to mitigate the risks that they are exposed to.[65] Ensuring early communication and balancing between disruption and consumer choice will be vital for a successful transition to low-carbon heating.

Gas grid blending: Low-level blending of low-carbon hydrogen into the existing natural gas grid could be a potential short-term transitional use for low-carbon hydrogen to enable rapid scaling up of low-carbon hydrogen demand. A Health and Safety Executive report concluded that the existing gas grid is able to accept up to 20% of hydrogen without any increased risk.[66] A 20% blend of low-carbon hydrogen is estimated to reduce emissions at the point of use by about 6–7%, as hydrogen has a lower energy density by volume than natural gas.[67] As a short-term measure, blending may not be the best use of available low-carbon hydrogen, which will be limited in the near future, particularly given that some of the uses detailed thus far lack a low-carbon alternative to hydrogen (eg some industrial processes). There will also be risks of higher consumer costs due to the high production cost of low-carbon hydrogen and of locking in demand for gas boilers, which may delay significant heat decarbonisation via the portfolio of measures outlined above.[68] However, with the appropriate commercial models and regulation, blending hydrogen into the existing gas grid could offer a potential benefit to scaling up the hydrogen value chain – that is, by creating an ‘offtaker of last resort’ with a ‘floor price’ for hydrogen. Low-carbon hydrogen producers would be allowed to inject excess hydrogen into the gas grid, and the hydrogen could be paid for at a minimum rate. This could reduce the risk for investors in hydrogen production by providing a constant demand.

A whole-system perspective

The decision on the best use of available low-carbon hydrogen needs to be made from a whole-system decarbonisation point of view; this approach also considers the counterfactuals in a simultaneous analysis. The use of hydrogen especially in those end uses that can achieve the highest carbon savings and cost efficiencies from a whole-system perspective should be supported by investment in rapid and early pilot projects to prove feasibility, address outstanding uncertainties, drive down costs to enable the transition, and support industry adoption.[69]

Discussion box: Hydrogen deployment beyond pilot-scale projects

Beyond the scale of pilot projects, there is a range of risks that need to be carefully managed when scaling up the role of hydrogen within the energy system. The ultimate strategy chosen will have implications for the ultimate end uses in which hydrogen will play a role.

Given that the availability of low-carbon hydrogen will be limited while production capacity is scaled up, there is a need to ensure the best use of hydrogen from the point of decarbonisation of the energy system as a whole. Demand for low-carbon hydrogen must also stay in line with the scale up of *blue* and *green hydrogen* production and supply, and the enabling infrastructure these require. If policies anticipate the availability of low-carbon hydrogen, but supply and the enabling infrastructure are unable to scale up at sufficient pace to meet this demand, emissions reduction could then be delayed as energy demands are met by high-carbon energy sources. This leads some to argue for an approach that actively directs the deployment of hydrogen to end uses where there is no alternative or better decarbonisation option. This approach could avoid infrastructure and emission lock-ins for end uses where there are alternative decarbonisation options that could achieve emission reductions more rapidly and at a lower cost.

However, the above risks must be balanced against the need to rapidly scale up the production of low-carbon hydrogen, the enabling infrastructure, supply chains, skills, and services needed for its production and use. Growing this ecosystem requires rapidly growing demand and markets for low-carbon hydrogen. Actively managing or limiting the available low-carbon hydrogen to specific end uses risks limiting the ‘demand pull’ created for the rapid scale up of low-carbon hydrogen production by not including other end uses, such as widespread use of hydrogen in domestic heating. It also risks overlooking the potential longer-term benefits available from wider hydrogen deployment.

42% of the domestic natural gas demand is within the six major industrial regions in the UK.[70] Many of these industrial regions are producing and consuming *grey hydrogen* at scale, and some of them have started transitioning to blue and/or green hydrogen. This, some argue, presents the opportunity to connect these industrial clusters to a dedicated transmission system and a repurposed national gas grid for hydrogen. This could become a national system to deliver hydrogen to areas of significant demand and, ultimately, all current gas grid locations for domestic heating. Furthermore, *electrolysers*, hydrogen storage, and hydrogen-ready *gas turbines* could provide the connection between gas and electricity distribution systems. Integrating the two energy systems could improve the whole-system flexibility and decarbonise the whole energy system more cost effectively.[71]

As above, the key risk in this approach, with its wider range of hydrogen distribution and end use, is that policies anticipate the availability of low-carbon hydrogen for these applications, such as domestic heating, but supply and the enabling infrastructure, supply chains, skills, and services are unable to scale up at sufficient pace to meet this need, with emissions reduction being delayed as a result. In this case,

continued over…

the widespread use of hydrogen for end uses such as domestic heating may lead to insufficient low-carbon hydrogen for other end uses where there are no alternative or better decarbonisation options, locking in emissions until low-carbon hydrogen is sufficiently available.

A strategy that maximises the production of low-carbon hydrogen while also managing the risks outlined above is required. This will require a region-specific approach to developing local hydrogen economies. As the current production and use of *grey hydrogen* are mainly within industrial clusters, low-carbon hydrogen production and use should focus on those areas. When low-carbon production capacity (and the enabling infrastructure this requires) has been sufficiently scaled up in these clusters, hydrogen deployment can be expanded from these industrial clusters for more widespread use in the energy system. Provided this expansion only takes place in line with the capacity for low-carbon hydrogen production, the risks outlined above should be sufficiently managed. This means that, subject to regional variations such as the cost and efficiencies of low-carbon hydrogen production, storage, and transportation, the availability of low-carbon hydrogen over time, and the development of other decarbonisation options for different end uses, the degree of hydrogen deployment will vary significantly across different regions.

While this Discussion Box focusses on the technical and infrastructure issues and dependencies in the roll-out of low-carbon hydrogen, as touched upon elsewhere in this report, there are other social, economic and political risks to different hydrogen deployment pathways which will need to be considered. These include consumer preferences and response, wider public acceptability, and the coordination and economics of roll-out and financing.

A bus fully powered by hydrogen gas in London, England. United Kingdom

Section 3: Low-carbon hydrogen production methods and the associated risks and dependencies

As described in Section 2, hydrogen has significant potential in certain sectors to become the best or only option available. However, scaling up low-carbon hydrogen production in such a short time frame bears many risks and dependencies, as described in detail in the present section. It is vital to recognise and manage these risks and dependencies during the process of scaling up hydrogen's role in the energy system in order to deliver rapid emissions reduction and maximise the whole-system benefits that are achievable.

Hydrogen production methods

The many 'colours' of hydrogen: While this report focuses on the two low-carbon hydrogen production methods (so-called 'blue' and 'green') that are predicted to be the most prevalent, Table 3.1 gives an overview of the different hydrogen production methods depending on the energy source, feedstock, and technology. (assigned and denoted with different colours; other less substantial production methods are not included).

Need for a hydrogen standard: The scaling up of different hydrogen production methods poses a risk of over complicating the decision-making process. The UK government is developing a low-carbon hydrogen standard, which will become the threshold for qualifying as low-carbon hydrogen production and for access to financial support. A focus on lifecycle carbon intensity is required, expressed in grams of CO_2-equivalent per megajoule (gCO_2e/MJ) LHV (lower heating value) measuring the greenhouse gas intensity per heating value of hydrogen.[73] This is a technology-neutral, outcome-oriented criterion to assess the hydrogen emission footprint. It also opens a debate about competition between different hydrogen production routes that meet the required carbon intensity at least cost.[74] For monitoring and verification purposes, the standard must adopt robust estimates of upstream natural gas leakages, carbon capture rates, and reservoir leakages to estimate the greenhouse gas emission impact and, hence, avoid the risk of underperformance, even with ambitious standards.[75] Carbon intensity of electricity used for *electrolysis* also needs to be assessed. In addition to the simple threshold, the government is considering a greenhouse gas-intensity certification scheme that would allow customers to know the footprint of a quantity of hydrogen.

Biomass gasification: One hydrogen production method that has not been assigned a colour is '*biomass gasification*'. This is a controlled heating process to convert biomass into a mixture of gases including hydrogen and CO_2. Because growing biomass removes CO_2 from the atmosphere, if this method is coupled with *CCS*, it could lead to hydrogen production with no or negative carbon emissions.[76] However, *BECCS* is unproven at a commercial scale with risks of questionable

Terminology		Technology	Feedstock/ Energy source	Greenhouse gas footprint*
Production via electricity	***Green hydrogen***	*Electrolysis*	Renewables such as wind, solar, hydro, tidal, geothermal	Minimal
	Pink hydrogen		Nuclear	
	Yellow hydrogen		Mixed-origin grid energy	Medium
Production via fossil fuels	***Blue hydrogen***	*Autothermal reforming, steam methane reforming or coal gasification + CCS*	Natural gas or coal	Low
	Turquoise hydrogen	*Pyrolysis*	Natural gas	Minimal to low (Solid carbon as by-product)
	Grey hydrogen	*Autothermal reforming or steam methane reforming*		Medium
	Brown hydrogen	*Coal gasification*	Brown coal (lignite)	High
	Black hydrogen	*Coal gasification*	Black coal	
Production via biomass	**'Unassigned'**	*Biomass gasification + CCS*	Biomass	Potentially negative

* 'Greenhouse gas footprint' given as an indicative guide, but each category can be higher in some cases.

Table 3.1. | The hydrogen colour spectrum[72]

carbon neutrality (depending on the practices for producing the biomass and the actual capture rates of the CCS). There are also risks to forest biodiversity, potential land use tensions with food production and other land uses, and other sustainability issues.[77] To utilise BECCS to achieve hydrogen production with negative emissions, tighter bioenergy supply chain emissions regulations are required for robust monitoring and verification. The government should also consider separating out the net zero target into 'reduction' and 'removal'. The removal target should establish the negative emissions required to reach the overall target of net zero emissions. It should be subject to regular review to expand the role of removals if current ambiguities around BECCS performance, which are currently masked behind commercial confidentiality concerns, can be addressed.[78]

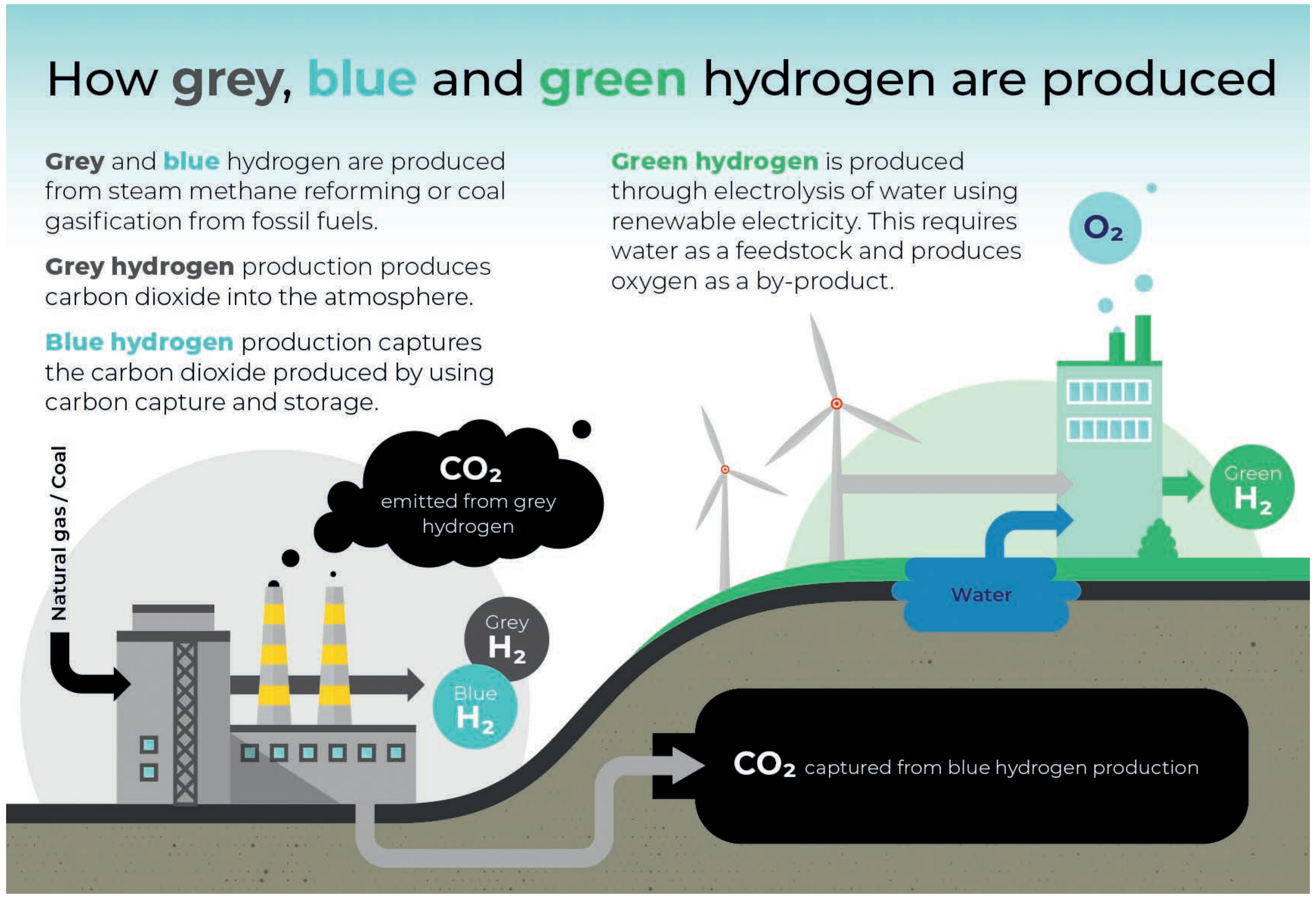


Figure 3.1. | Grey, blue and green hydrogen production methods

Production of grey, blue, and green hydrogen

See Figure 3.1.

Amount and proportion of blue and green hydrogen required to meet energy demand

The *CCC's Sixth Carbon Budget* recommended scenario – the Balanced Net Zero Pathway – estimated that three quarters of hydrogen produced in 2050 would be *blue* and *green hydrogen* (see also Table 3.2).[79] However, the production processes for both blue and green hydrogen are highly dependent on the factors detailed in the following sections.

Production method	TWh/year	Proportion
Electrolysis	97.20	44%
Fossil gas + *CCS*	71.00	31%
Biomass + *CCS*	24.94	11%
Imports	29.53	13%

Table 3.2. | Amount and proportion of hydrogen supply in 2050[80]

Blue hydrogen risks and dependencies

Dependence on CCS technology: A cost-effective scaling up of *CCS* technology and capacity is essential for *blue hydrogen* production to capture and sequester the CO_2 produced in the process.[81] All CCS projects in the UK are still in the development phase and the current UK CO_2 storage capacity is zero. It is claimed that the CO_2 emissions capture rate could be up to 98%.[82] A 99.9% capture rate has been achieved by the Tomakomai CCS Demonstration Project in Japan[83] however, there is still a risk of capture rates being lower in practice elsewhere. For example, the only hydrogen facility currently sequestering the captured CO_2, the Quest plant in Canada built in 2015, reported a capture rate of 80% in its first operating year.[84] In terms of capacity, it is expected that between 1 and 52 $MtCO_2$ per annum[85] of CCS capacity will be needed in the UK for blue hydrogen production in 2050.[86] For comparison, the current global CCS capacity is at 40 $MtCO_2$. While the government has committed to four CCS clusters, capturing and storing 20–30 $MtCO_2$ annually by 2030[87], the scale up of CCS must be proportionate with that of blue hydrogen production to ensure sufficient capacity, including the capture rates required to capture and store carbon produced from hydrogen production.

Dependence on fossil fuel supply: The *CCC* estimated that between 6 and 240 TWh[88] of hydrogen will be produced from natural gas with *CCS* in 2050.[89] Assuming an 80% methane reformer efficiency, 7–300 TWh of natural gas would be needed. To put this into context, that could be about 1.3 times the amount of natural gas used for electricity generation in 2020 (231.6 TWh) or 2–80% of the natural gas produced in the UK in 2020.[90] Fossil fuel price is the largest cost component for blue hydrogen production, meaning that the cost of blue hydrogen production will be directly impacted by international market fluctuations.[91] In terms of energy security, due to blue hydrogen's direct reliance on global natural gas supply, it is exposed to the same supply and market volatility concerns as natural gas caused by geopolitical issues. The scale up of blue hydrogen production could also pose a risk of locking in demand for new fossil fuel extraction projects. The International Energy Agency (IEA) has indicated that, to meet net zero by 2050 and to limit global warming within 1.5°C, there should not be investment in new fossil fuel supply.[92] The government needs to safeguard the UK's energy security by diversification of global natural gas supply and energy sources, manage the level of fossil fuel extraction, and enable the transition of the fossil fuel industry to the key technologies that could tackle emissions, such as hydrogen, CCS, and offshore wind.

Fugitive emissions from production processes: Processes of fossil fuel extraction and *blue hydrogen* production, storage, and transport lead to *fugitive emissions* of mainly *methane*. Reducing fugitive emissions is particularly challenging owing to a number of barriers, including that there is an information gap caused by insufficient measurement and reporting; new infrastructure or existing assets would need to be constructed or upgraded to reduce methane emissions; and there is a lack of incentives for investment, as the environmental costs of pollution are not factored in.[93] Policy actions are required to reduce fugitive emissions across the whole value chain of blue hydrogen production, and should be governed by stringent low-carbon hydrogen standards for it to be a viable decarbonisation option. Investing in methane emissions reduction is also one of the quickest ways to reduce global temperature rises, and will simultaneously reduce emissions from the fossil fuels supply chain.[94] As such, regulators should be sufficiently resourced with the capability needed for effective enforcement.

Green hydrogen risks and dependencies

Dependence on renewable electricity generation and supply: *Green hydrogen* production depends on *electrolysis* using renewable electricity and therefore depends on significant expansion of the UK's renewable energy capacity.[95] It is estimated that 60–218 TWh/year of electricity in 2050 (10–24% of total electricity demand in 2050)[96] would be used for green hydrogen production in the UK, equivalent to 70–250% of variable renewable capacity in 2020 (88 TWh).[97] To put this into context, the UK would need to build wind farms with the capacity of 15–60 GW, equivalent to around two to six times of the UK's current operational windfarm capacity (10 GW),[98] only to supply renewable electricity for producing green hydrogen in 2050. The scale up of renewable capacity must take into account this demand to ensure sufficient low-carbon electricity for green hydrogen production. The government has rightly committed to decarbonise the electricity system by 2035,[99] and the focus now must be on delivery and implementation with a comprehensive strategy that incorporates the future demands for renewable electricity, including that for green hydrogen production and the increasing electrification of the overall energy demand.

Pilot scale hydrogen production project in Hastings, Victoria. Australia

Competition for renewable energy between direct electrification and green hydrogen production: *Green hydrogen* will be well suited in future electricity grids with high renewable energy capacity. The ability to store renewable energy in the form of hydrogen for use when renewable generation such as sun and wind are not available enables renewables to deliver more clean electricity. However, as the UK's electricity grid is still in a transitional phase to greater renewable sources of generation, connecting *electrolysers* to the grid may lead to a temporary ramping up of the dispatchable generation (mainly gas and coal electricity generation) required to service the increase in demand and a delay in phasing out of fossil fuel electricity generation. In this scenario, the resultant hydrogen could be as carbon intensive as *grey hydrogen*.[100] The competition for renewable energy capacity also poses a risk of hampering efforts in other areas to decarbonise via direct electrification, which is the most efficient use of low-carbon electricity and is estimated to be needed for the abatement of 38% of the UK's emissions by 2050.[101] There is a need to safeguard the transition to renewable electricity generation while, in parallel, creating the conditions for future large-scale green hydrogen production. To achieve this, electrolysers could be designed into the system to serve as flexible demand-side resources that can be ramped up and down or turned off depending on levels of demand and the CO_2 emissions intensity of the national power mix at any one time. Power purchase agreements with grid-connected renewable electricity generators could be utilised to ensure the emission threshold of the electricity the electrolysers consume. This could make green hydrogen an additional driver for the scaling up of renewable energy generation capacity.[102]

Electrolyser build rates and supply of the critical raw materials required: The scale up of *green hydrogen* is dependent on *electrolyser* build rates and the supply of the critical raw materials required (eg platinum, iridium, and yttrium). German research (with similar figures to the UK) shows most of these materials are subject to a moderate to high supply risk.[103] The supply of these critical raw materials is heavily dependent on a limited number of countries, as shown in Figure 3.2. Rising global demand could cause price fluctuations and potentially lead to geopolitical issues. Actions to build a *circular economy* could help address the supply risks and minimise the impact of price fluctuations. These include implementing *resource efficiency* measures to improve recyclability and reduce the use of these critical raw materials in electrolyser design and investing in infrastructure for the circular economy to retain the value of these materials.[104]

Water supply dependency and environmental impact: *Green hydrogen* production requires a significant amount of water as a feedstock. Although the UK is classified with a low water stress level,[106] desalination of seawater may be required to meet the demand from green hydrogen, which produces concentrated brine as waste that, in turn, will cause ecological effects if it is returned to the sea.[107] Access to sufficient water supply and sufficient waste management systems together with availability and access to renewable electricity are crucial factors in determining the location and environmental impact of green hydrogen production.

Wider hydrogen value chain risks and dependencies

Blue and green hydrogen competition: Currently, *blue hydrogen* is cheaper to produce than *green hydrogen* because, except *CCS*, the underlying technologies are commercially mature. The cost of blue hydrogen production may only fall by 10%,[108] as the cost of natural gas is the largest cost component in a high gas price scenario (USD $11/MMBtu), followed by capital expenditure and operating expenditure.[109] (This cost projection was conducted before the war in Ukraine and does not account for its impact on international gas supply and prices.) For green hydrogen, although it is expensive to produce today, due to the rapid scaling up of *electrolysers* and declining cost of renewable electricity generation, its cost could drop as much as 75% by 2030, outcompeting blue hydrogen.[110] The UK government is co-leading a 'clean hydrogen mission' with Australia, Chile, the European Union, and the US, aiming to reduce the end-to-end costs of green hydrogen to USD $2/kg by 2030.[111] There is a need for the government to consider, from a whole-system and energy security perspective, the contributions of blue and green hydrogen

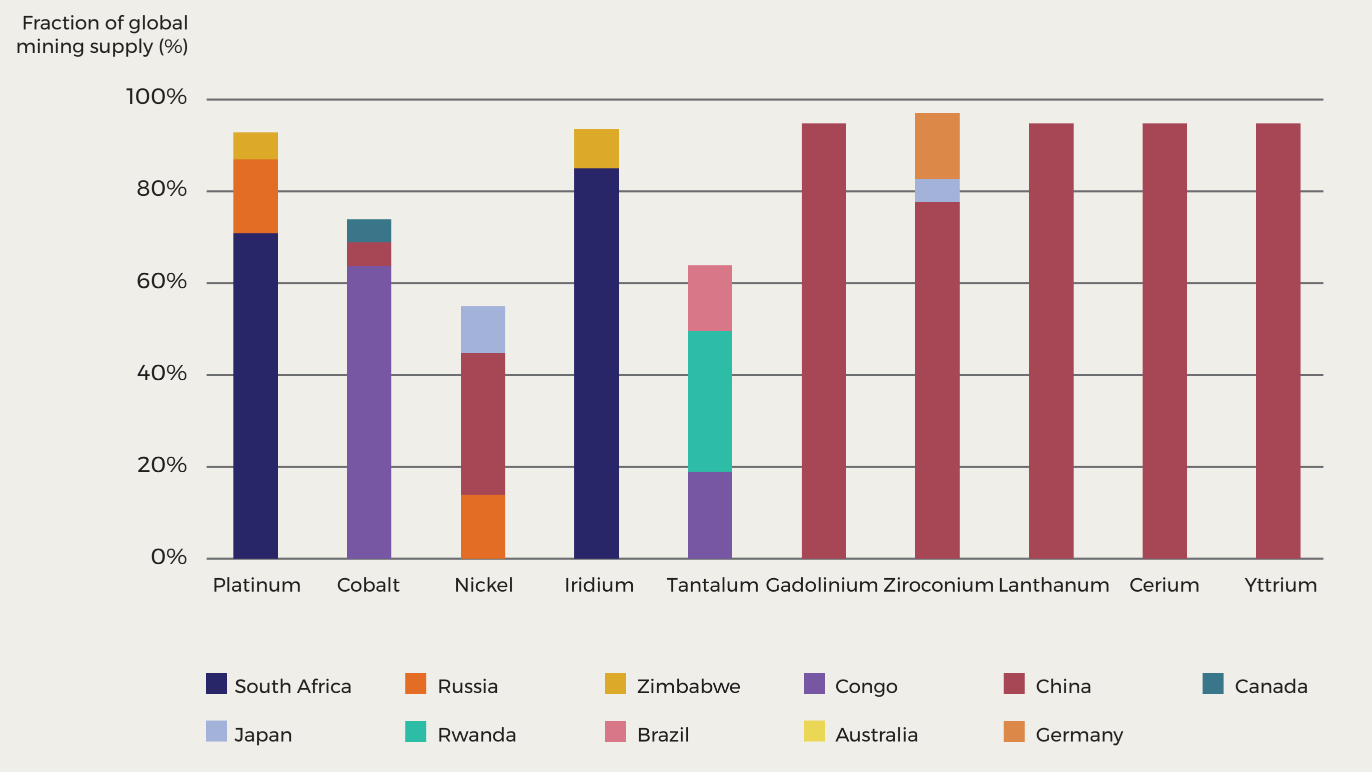
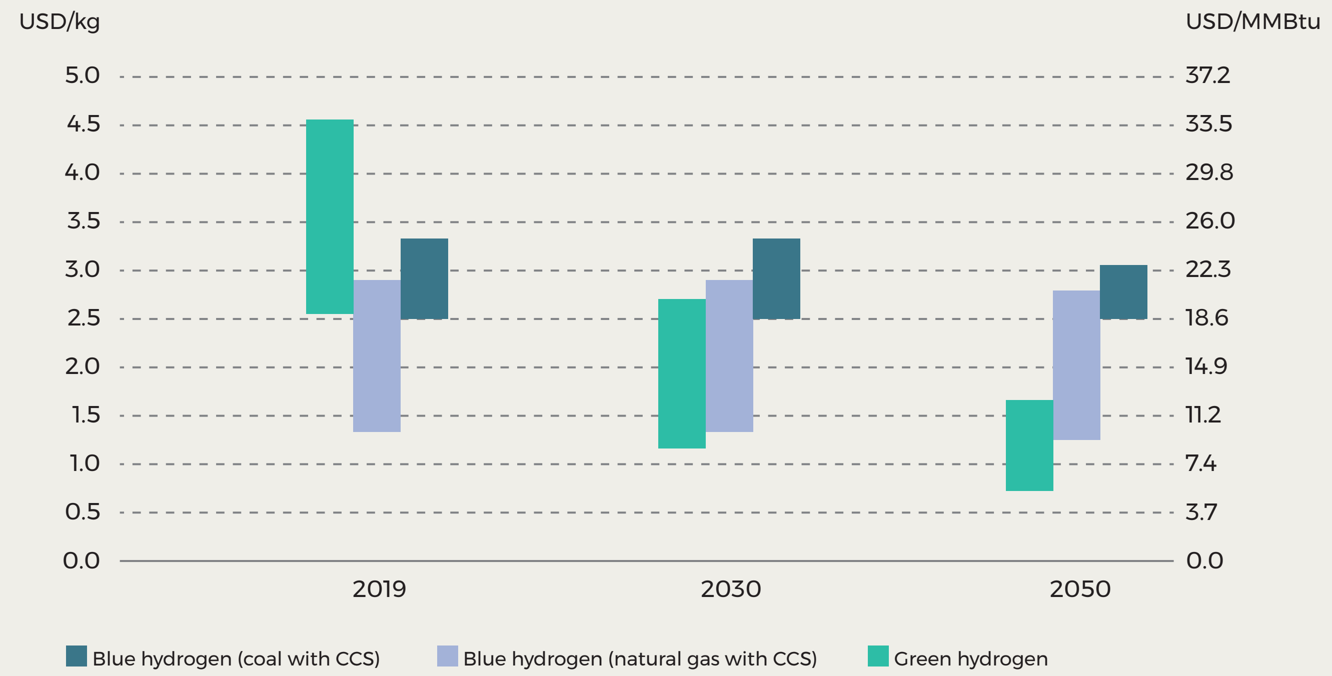


Figure 3.2. | Top producers of critical materials in electrolysers[105]



Note: Green hydrogen costs based on large projects with optimistic projections for capex. Natural gas prices range from $1.1–10.3/MMBtu, coal from $30–116/t.

Figure 3.3. | Forecast global range of the levelised cost of hydrogen production from large projects[113]

Discussion box: Proportion of blue and green hydrogen in meeting the UK government's 10 GW 2030 interim target and net zero by 2050

Both *blue* and *green hydrogen* could contribute to meeting the government's 10 GW 2030 target and net zero by 2050. However, the amounts that blue and green hydrogen contribute in practice will depend on a number of factors.

Given that 96% of the UK's existing hydrogen production capacity (around 0.7 Mt, 27 TWh/year) is *grey hydrogen*,[114] coupling *CCS* with the existing grey hydrogen production capacity to convert it into blue hydrogen could be a pragmatic way to contribute to meeting the government's 10 GW (84 TWh) 2030 target for low-carbon hydrogen. The conversion could accelerate the development of CCS technology, the hydrogen value chain, and the associated infrastructure.

However, blue hydrogen's dependence on natural gas as the major feedstock will expose its production to international natural gas price fluctuations and supply issues. Achieving blue hydrogen production is also dependent on the successful scale up and performance of CCS. The current cost of green hydrogen production may be higher than that of blue hydrogen, but it is forecasted to fall to a level that is cheaper than blue hydrogen over time. As the cost of green hydrogen falls, blue hydrogen is likely to be valued to the extent that it can contribute to demand matching and can diversify the sources of energy to produce low-carbon hydrogen. But, ultimately, there is a potential risk that blue hydrogen production infrastructure could become stranded assets in the future if green hydrogen production capacity is sufficiently scaled up to meet the overall demand for low-carbon hydrogen.

The government has targeted 1 GW of *electrolysers* by 2025 and at least half of the 10 GW 2030 interim target to be met with green hydrogen.[115] While scaling up blue hydrogen involves large investments that are coupled with CCS technology in industrial clusters, green hydrogen can start at a small scale and grow in project size and number. Green hydrogen production could be co-located with critical hydrogen-powered infrastructure to improve energy security and resilience. Scaling up green hydrogen production could act as an additional driver to accelerate the scale up of renewable electricity generation and could avoid the risks associated with blue hydrogen production infrastructure – namely, fossil fuel supply and CCS dependencies as well as *fugitive emissions* from the production processes.

However, a higher green hydrogen pathway is not without its risks. Green hydrogen production is dependent on increased renewable electricity generation and supply and electrolyser development, including build rates and the supply of the critical raw materials required. Both could be a barrier for rapid scaling up in a short time frame. Green hydrogen production is also subject to the intermittency of renewable electricity generation. More hydrogen storage and blue hydrogen production capacity (for demand matching) would be required to balance the effect of this and improve system resilience.

To realise the potential benefits and manage the risks of scaling up blue and green hydrogen, the proportion of blue and green hydrogen in meeting the government's 10 GW 2030 interim target and net zero by 2050 should be considered from a whole-system perspective. A pragmatic way to achieve the government's 2030 target is likely to comprise turning the existing grey hydrogen production capacity to blue hydrogen with sufficient CCS capacity, supporting the scale up of green hydrogen production in parallel, and deducing the target for blue hydrogen production by balancing the production cost between blue and green hydrogen and the availability and performance of CCS for blue hydrogen production over time.

to meeting its 2030 interim target of 10 GW (84 TWh) low-carbon hydrogen production[112] and achieving net zero by 2050. Major factors to take into account are the decision on phasing out, or converting the existing *grey hydrogen* production capacity to blue hydrogen by coupling with CCS; the foreseeable cost and supply of natural gas; the scale up and availability of CCS for blue hydrogen production; and the scale up and availability of renewable energy and electrolysers for green hydrogen production.

Scaling up the 'chicken' and the 'egg': Scaling up hydrogen from production through to end use would involve many uncertainties across complex value chains. This makes effective coordination of deployment difficult and risks a 'chicken-and-egg' situation.[116] Policy interventions are needed to scale up the hydrogen value chain across production, transportation, storage, and end use by stimulating the demand for hydrogen and addressing the investment risks of first movers to reach the minimum economies of scale for market penetration.[117]

Markets and regulations: Markets and regulations both nationally and internationally have a key role to play in actively driving forward safe, trusted, and joined-up adoption and roll-out of hydrogen technologies. The readiness and willingness to adapt to markets and regulations will affect the uptake of hydrogen and the UK's ability to integrate hydrogen into the energy system.

Safety and public trust: Hydrogen uptake is dependent on the safety of and public trust in the technologies across the supply chain, and therefore on the trustworthiness of standard setting and regulations. Continued trials and demonstrations at scale – for example, through the community trials of hydrogen that are being undertaken by gas distribution network companies[118] – are required to provide sufficient thorough safety assessments and to understand the health and safety implications of the increase in the use of hydrogen in society. Safety standards must be established and effectively regulated, as natural gas use is today.[119] In the 2020 Climate Assembly, 83% of the participants 'strongly agreed' or 'agreed' that hydrogen should be part of the solution for zero carbon heating (along with 80% for heat pumps and heat networks, respectively), and 94% of the participants 'strongly agreed' or 'agreed' that different solutions for zero carbon heating should be offered to people in different parts of the country.[120] Further extensive public engagement is needed to understand and address the perspectives and possible concerns of different stakeholders and to build public trust.[121]

Skills gaps: The hydrogen value chain (from production to transportation, storage, and end use) and its associated technologies, such as *CCS* and *electrolysers*, are still emerging sectors and the primary skills gaps must be addressed to enable wide-scale deployment of these key technologies. Some studies have suggested that the UK's offshore oil and gas workforce can expect to have a medium transferability to *blue hydrogen* and CCS.[122] For *green hydrogen* production, skill sets are similar to the chemical industry, and only minor upskilling will be needed.[123] However, for both blue and green hydrogen production, further research is required to understand the skills gaps and address them by sufficiently upskilling the workforce for these emerging sectors.

Resource efficiency and embodied carbon in infrastructure: The scaling up of hydrogen value chains will require new infrastructure to be built. A recent Net Zero Infrastructure Industry Coalition report highlighted that infrastructure emissions account for more than half of the UK's carbon footprint and that current infrastructure plans are a major risk to net zero delivery.[124] Currently, there are few policies in place to improve *resource efficiency* and incentivise the use of low-carbon materials within the construction industry. Standardised approaches to calculating *embodied carbon* are largely voluntary. Regulations and standards will be key to minimising *operational carbon* at the construction stage and embodied carbon in the required infrastructure.[125]

Atmospheric greenhouse effect of hydrogen leakages: A recent study commissioned by the UK government found that hydrogen leakage into the atmosphere is likely to have an indirect but linear impact on atmospheric greenhouse effect.[126] Hydrogen leakage is likely to cause an increase in *methane*, water vapour, and tropospheric ozone, which all contribute to the greenhouse effect. The global warming potential over a 100-year period of hydrogen is estimated to be double that from previous published calculations.[127] Therefore, hydrogen leakage poses a risk of partially offsetting the climate benefits of substituting fossil fuels with low-carbon hydrogen. Hydrogen leakages during production, storage, transportation, and use must be minimised to uphold hydrogen's value for decarbonisation as the use of hydrogen becomes increasingly widespread in the future.

Global production and use of hydrogen and international trade: With declining costs of renewables such as solar and wind power, building *electrolysers* at locations with abundant renewable resources could be a low-cost supply option for low-carbon hydrogen, even after including the transportation and storage costs of transporting hydrogen from remote renewables locations to end uses.[128] Moreover, the possibility of importing hydrogen from various locations worldwide and the differences between the global supply chains for natural gas and hydrogen could present an opportunity to diversify energy supply, thereby improving energy security. The ambitions for hydrogen of other governments internationally will have a significant impact on the global economies of scale, learnings, and international trade and markets. Standards and certification mechanisms at an international level could establish a level playing field by enabling effective cross-border trade and providing certainty for investors.[129] This could drive down the cost of hydrogen trading and stimulate hydrogen development (see also Figure 3.4).

Cost uncertainties of hydrogen imports: The cost of hydrogen imports is uncertain as the global market is still in its infancy. Currently, about 85% of hydrogen gas is produced and consumed on-site within a facility.[131] Because hydrogen is an extremely small and highly reactive element, it is difficult to store and transport efficiently.

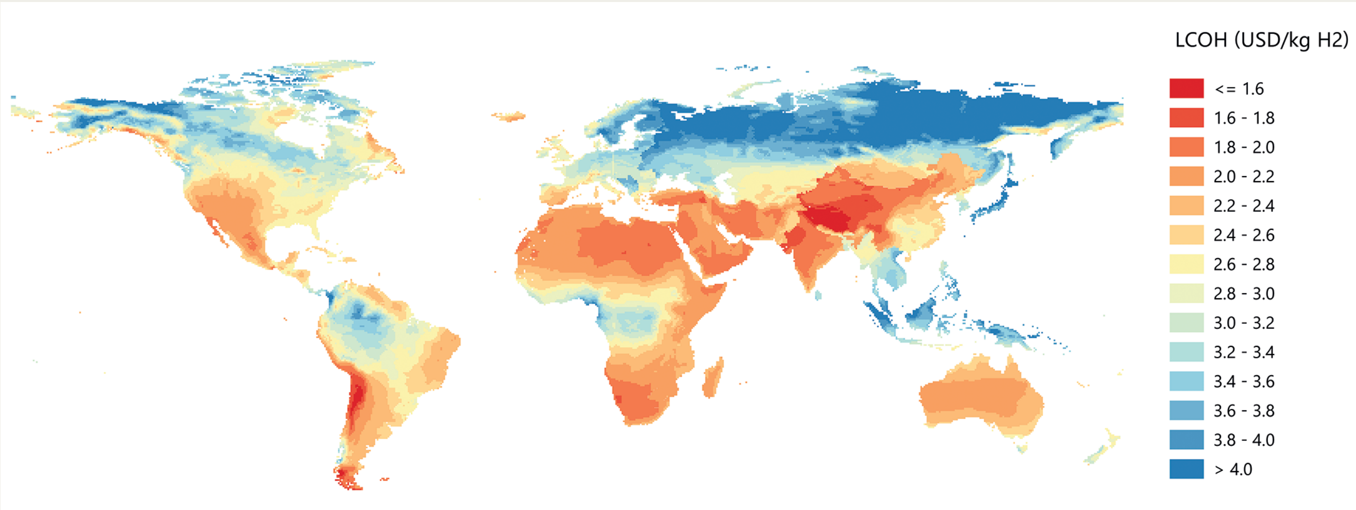
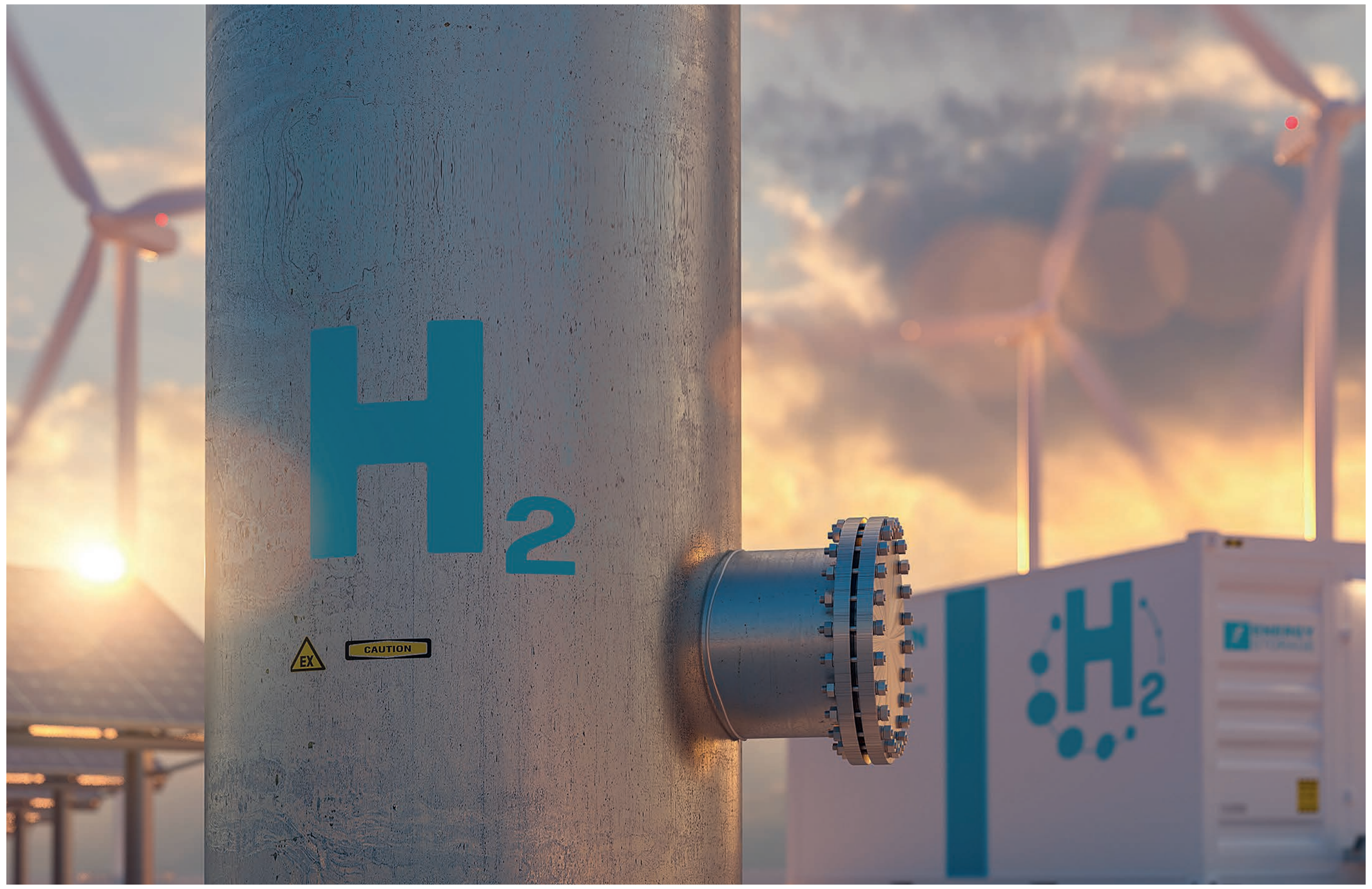


Figure 3.4. | Hydrogen costs from hybrid solar PV and onshore wind systems in the long term[130]

Note 1: LCOH = Levelised cost of hydrogen
Note 2: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city, or area.

Significant cost of transportation makes consuming hydrogen as close to production as possible the cheapest option.[132] However, if hydrogen needs to be transported, the two main options are pipelines and ships. Where feasible, new and repurposed pipelines are likely to be more cost effective than ships. Shipping is technically possible for long-distance transport where pipelines are not available. Owing to hydrogen's low energy density by volume, it is more efficient to convert gaseous hydrogen to a more energy-dense liquid form such as liquid hydrogen, liquid organic hydrogen carriers, and ammonia prior to transportation. Available studies suggest that the most promising carrier is ammonia, because it is already an internationally traded commodity and could be used directly as feedstock or fuel without converting it back to hydrogen.[133] However, conversion to ammonia would produce CO_2, and, hence, would require additional *CCS*. Considering the cost uncertainties of hydrogen imports, the UK should focus on scaling up local hydrogen production to meet most of its future hydrogen demand and evaluate emerging global supply opportunities as the global hydrogen market develops.

Emission uncertainties of hydrogen imports: As with other global supply chains, the UK may not have direct control over the regulations and standards governing international supply chains, which, if strict low-carbon hydrogen standards are not adhered to, introduces the risk of offshoring emissions. A lack of regulations and standards could lead to widespread *grey hydrogen* production to meet the market demand. The resulting emissions could be higher than those from direct burning of natural gas. Wide-scale adoption and proper enforcement of low-carbon hydrogen standards such as the one under development in the UK would be an appropriate mechanism with which to regulate the carbon content of hydrogen imports.



Section 4: **Policy recommendations for the government to ensure that the benefits of hydrogen for a net zero energy system are realised**

Hydrogen is likely to be the most effective or the only decarbonisation option for some end uses – for example, in certain industrial direct-firing processes. Therefore, it will play a critical role in any net zero energy system. This makes significant upscaling of low-carbon hydrogen production, transportation, storage, and end use in the short to medium term essential to establish the infrastructure and value chains for wider hydrogen applications.

While the best way to drive an uplift in low-carbon hydrogen production is to maximise demand in all its end uses, in doing so, a clear decision-making process is needed to realise the potential roles of hydrogen and ensure supply in the end uses where hydrogen is most likely the best or only low-carbon option available, thereby offering the greatest value to decarbonisation of the whole energy system.

The UK risks not meeting its Fifth and *Sixth Carbon Budgets* and falling behind international competitors if the remaining uncertainties are not addressed soon. The government must therefore prioritise rapid and early pilot projects to provide sufficient evidence for addressing the remaining uncertainties and deducing the decision-making process for low-carbon hydrogen deployment.

The government must capture the opportunities presented by low-carbon hydrogen to make best use of its potential and scale up the low-carbon hydrogen system while managing the risks and dependencies involved. Two overarching requirements, described in Table 4.1 and Table 4.2, set out what policies need to achieve – now and over the next five years – if low-carbon hydrogen is to be successfully scaled up as part of a net zero energy system.

Requirement 1: Achieve a rapid scaling up of the low-carbon hydrogen infrastructure - with particular attention to those end uses for which hydrogen deployment offers the greatest value to decarbonisation of the whole energy system

NOW	NEXT (WITHIN THE NEXT FIVE YEARS)
Invest in rapid and early pilot projects to provide sufficient evidence to determine the hydrogen end uses that can achieve the highest carbon savings and cost efficiencies from a whole-system perspective. These can address all outstanding uncertainties, drive down costs to enable the transition, and, thus, support industry adoption.	Develop and implement an ambitious but pragmatic roadmap for how low-carbon hydrogen production is to be scaled up to meet demand, with details about the contributions of each type of hydrogen production, including taking a whole-system approach to the scaling up of key requisite technologies (ie *CCS*, renewable electricity generation, and *electrolysers*).
Finalise the hydrogen business model in 2022 as committed in the UK's hydrogen strategy.[134] This should also identify areas that require outcome-based market interventions, such as subsidies and auctions to reduce costs, frontload investment, stimulate innovation, development, and deployment, and minimise the risks of investment.	Ensure low-carbon hydrogen is available for the end uses in which hydrogen deployment has the potential to become the best or only low-/zero-carbon option available. This will maximise hydrogen's value to decarbonisation of the whole energy system and close the emissions gap to put the UK on track with its Fifth and *Sixth Carbon Budgets* and the 2050 net zero target.

Table 4.1.

Requirement 2: Manage the risks and dependencies when scaling up hydrogen value chains

NOW	NEXT (WITHIN THE NEXT FIVE YEARS)
Wider hydrogen value chain	
Implement stringent, outcome-oriented low-carbon hydrogen standards that include emissions throughout the whole production and supply process to ensure a low level of CO_2 per unit of hydrogen. These standards must incentivise engineering solutions for leakages in hydrogen infrastructure to minimise the atmospheric greenhouse effects of hydrogen and apply to any imports to avoid the risk of offshoring emissions.	Address the primary skills gaps relating to the key technologies of *CCS*, renewable electricity generation, and hydrogen to enable wide-scale deployment. Further research should be undertaken to understand the skills gaps in detail, to develop a green skills strategy to sufficiently upskill the workforce for these emerging sectors, and to ensure a just transition for the UK's offshore energy workforce.
Build up all relevant regulators' capability to uphold robust enforcement and monitoring of crucial regulations, such as the low-carbon hydrogen standard, and to cope with the rapid scaling up of hydrogen value chains. Regulators should identify and develop regulatory and commercial frameworks accordingly as the hydrogen infrastructure and economy develops.	Consider a mandatory minimum whole-life carbon standard to minimise *operational* and *embodied carbon* at the construction stage for new hydrogen plants.
Investigate and ensure the safety of hydrogen through further safety assessments. Outcomes of the safety assessments shall be used to establish safety standards to safeguard health and safety as hydrogen production, transportation, storage, and end use scale up in society. At the same time, the government should ensure meaningful public engagement and stakeholder engagement as the hydrogen value chain develops.	Foster the development of globally assured standards and certification mechanisms to create the conditions for an international market in low-carbon hydrogen.
Blue hydrogen	
Ensure sufficient domestic CCS capacity to meet the CO_2 capture requirements for *blue hydrogen* production and other sectors by enabling the necessary infrastructure deployment and putting in place a robust monitoring regime to verify the emissions removals.	
Address the risks associated with the fossil fuel supply chain, including driving *fugitive emissions* reductions by improving measurement and reporting of emissions data (including process emissions and reservoir leakages) and by imposing the environmental costs of pollution (eg carbon tax). This will enable efficient regulatory interventions and incentivise investment in *methane* emissions reduction.	
Green hydrogen	
Safeguard the electricity transition while in parallel creating the conditions for future large-scale *green hydrogen* production. The enabling policy interventions must ensure and catalyse additional deployment of renewable electricity to meet the demand for green hydrogen production.	Invest in research and innovation to reduce or ultimately remove the need for critical scarce materials within *electrolysers*.
Manage the supply risks associated with critical scarce materials for electrolysers and other technologies, such as batteries, including design standards for *resource efficiency* to improve the lifetime and recyclability of electrolysers and/or the recovery and reuse of materials.	Commission further investigations on the implications of *electrolysis* at scale on water supply and waste management systems. Determine the impacts on water purification, supply, and wastewater production. These findings must be applied in determining the location of green hydrogen production.

Table 4.2.

Glossary

Term	Definition
Autothermal reforming	Steam methane reforming is a process in which energy is provided by introducing oxygen to burn part of the feedstock as opposed to separately burning natural gas to produce *syngas* (a mixture of natural gas, hydrogen, carbon monoxide, CO_2, and water), which is then further processed to separate the hydrogen
Basic oxygen furnace	Basic oxygen furnaces use pig iron and small amounts of scrap as their primary material inputs and typically melt the furnace charge with coke oven, blast furnace, and natural gas
Battery electric vehicle	A pure electric vehicle that exclusively uses chemical energy stored in rechargeable battery to power the electric motors for propulsion
BECCS	See *Bioenergy with carbon capture and storage*
BEV	See *Battery electric vehicle*
Bioenergy with carbon capture and storage	Refers to bioenergy processes (such as burning it for electricity) during which carbon is captured and stored. If carefully managed, using sustainable biomass, BECCS can generate 'negative emissions' because, while providing energy, it also captures and stores the atmospheric CO_2 that is absorbed by plants as they grow
Biomass gasification	A process in which biomass such as wood, straw, or waste is heated and pressurised with oxygen and steam to produce syngas
Blast furnace	A vertical tubular vessel used for smelting to produce industrial metals. For steelmaking, it uses coke, iron ore, and limestone to produce pig iron
Blue hydrogen	Blue hydrogen is produced from autothermal reforming, steam methane reforming, or coal gasification from fossil fuels (eg natural gas and coal), where the CO_2 produced during the production process is mostly abated using carbon capture and storage
Carbon budget	A carbon budget places a restriction on the total amount of greenhouse gases the UK can emit over a five-year period
Carbon capture and storage	The process of capturing CO_2 before it enters the atmosphere, transporting it and storing it. Usually, the CO_2 is captured from large point sources, such as a chemical plant or biomass power plant, and then stored in an underground geological formation
CCC	See *Climate Change Committee*
CCS	See *Carbon capture and storage*
Circular economy	A circular economy maximises the sustainable use and value of resources, eliminating waste and benefiting both the economy and the environment. It offers an alternative to the predominant current approach in which resources are used for one purpose and then discarded
Climate Change Committee (originally, the Committee on Climate Change)	The CCC is an independent statutory body established under the Climate Change Act 2008. It advises the UK government on emissions targets and reports to Parliament on progress made in reducing greenhouse gas emissions
Coal gasification	A process in which coal is heated and pressurised with oxygen and steam to produce syngas
Desulphurisation	The removal of sulphur or sulphur compounds, commonly from fuels such as natural gas, flue gas, coal, and oil. Hydrogen is used in one of the desulphurisation processes: 'hydrodesulphurisation'
Direct reduced iron	Direct reduced iron is produced from iron ore utilising either natural gas or hydrogen as the reducing agent
Electric arc furnace	A high-temperature furnace that uses high-voltage electric currents as its primary heating element. It is used for steelmaking wherein steel scrap is heated and melted by the heat of electric arcs striking between the furnace electrodes and the metal bath
Electrolyser	Equipment in which a chemical process (electrolysis) takes place that uses electricity to decompose water into hydrogen and oxygen
Electrolysis	A process that decomposes water into hydrogen and oxygen, taking place in an electrolyser and producing green hydrogen. It can be zero carbon if the electricity used is zero carbon
Embodied carbon	In the building lifecycle, embodied carbon is the CO_2e or greenhouse gas emissions associated with the non-operational phase of the project. This includes emissions cause by extraction, manufacture, transportation, assembly, maintenance, replacement, deconstruction, disposal, and end-of-life aspects of the materials and systems that make up a building
Energy vector	An energy vector allows the transfer, in space and time, of a quantity of energy, thereby making energy available for use at a distance of time and space from the source. The main energy vectors currently in use are fossil fuels, electricity, hydrogen, and heat-exchanging fluids

Excess electricity	Excess electricity arises when a system is unable to absorb the energy produced due to, for example, transmission constraints and insufficient demand without violating system security criteria
FCEV	See *Fuel cell electric vehicle*
Fertiliser production	The majority of ammonia produced through the Haber–Bosch process is used as fertiliser, in which hydrogen is an essential input for the process
Fuel cell electric vehicle	A fuel cell electric vehicle uses a fuel cell generating electricity to power the motor, generally using oxygen from the air and compressed hydrogen
Fugitive emissions	Emissions that unintentionally leak from underground pipelines and fossil fuel extraction activities – primarily, methane
Gas turbine	A type of continuous and internal combustion engine in which the blades of a turbine are driven by expanding hot gases produced from the combustion chamber by burning fuel. Gas turbines are used to power aircraft, trains, ships, electrical generators, pumps, gas compressors, and tanks
Green hydrogen	Produced through electrolysis of water using renewable electricity. This requires water as a feedstock and produces oxygen as a by-product
Grey hydrogen	Produced from autothermal reforming, steam methane reforming, or coal gasification from fossil fuels (eg natural gas and coal)
Haber–Bosch process	An industrial process of directly synthesising ammonia from hydrogen and nitrogen with a catalyst under high temperatures and pressure, developed by the German physical chemist Fritz Haber
Hydrocracking	A process by which the hydrocarbon molecules of petroleum are broken into simpler and smaller molecules, as gasoline or kerosene, by the addition of hydrogen under high pressure and with the presence of a catalyst
Hydrogen fuel cell	A fuel cell is an electrochemical cell that converts the chemical energy of a fuel and an oxidizing agent into electricity through a pair of redox reactions. A hydrogen fuel cell uses hydrogen as the fuel and oxygen as the oxidizing agent, which produces electricity, water, and heat as end products
Methane	Methane (CH_4) is a hydrocarbon that is a primary component of natural gas. It is the second most abundant anthropogenic greenhouse gas after CO_2, accounting for about 20% of global emissions
Operational carbon	In the building lifecycle, operational carbon is the CO_2e or greenhouse gas emissions associated with the maintenance and operation of the building. This includes emissions from heating, cooling, power, and providing water
Petroleum refining	Separates crude oil into components for a variety of purposes. The crude oil is heated and the hot gases are passed into the bottom of a distillation column. As the gases move up the height of the column, the gases cool below their boiling point and condense into a liquid such as gasoline, jet fuel, and diesel fuel. Hydrogen is used to lower the sulphur content of the fuels
Pyrolysis	The thermochemical decomposition of natural gas into hydrogen and solid carbon in an inert environment. It has not been proven at scale and is not economically viable compared to other hydrogen production methods
Resource efficiency	Resource efficiency means using the Earth's limited resources in a sustainable manner while minimising impacts on the environment
SAFs	See *Sustainable aviation fuels*
Sixth Carbon Budget	The Sixth Carbon Budget required under the Climate Change Act, published by the CCC, provides ministers with advice on the volume of greenhouse gases the UK can emit during the period 2033–2037. It also sets out the Balanced Net Zero Pathway for reaching net zero by 2050 and assesses key actions needed and milestones for key measures such as the phasing out and rolling out of key technologies
Specific energy	Specific energy or massic energy is energy per unit mass. It is also sometimes called gravimetric energy density
Steam methane reforming	A process in which methane from natural gas and steam are heated over a catalyst to produce syngas, which is then further processed to separate the hydrogen
Sustainable aviation fuels	Low-carbon alternatives to conventional, fossil-derived aviation fuel, or 'drop-in' equivalents that present similar characteristics to conventional jet fuel. Generally, the fuels can be produced from biomass, non-biogenic waste, and CO_2 with green hydrogen
Syngas	A mixture of natural gas, hydrogen, carbon monoxide, CO_2, and water
System balancing	A series of activities to balance between electricity production and demand to maintain a constant electricity frequency for stable electricity system operation

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