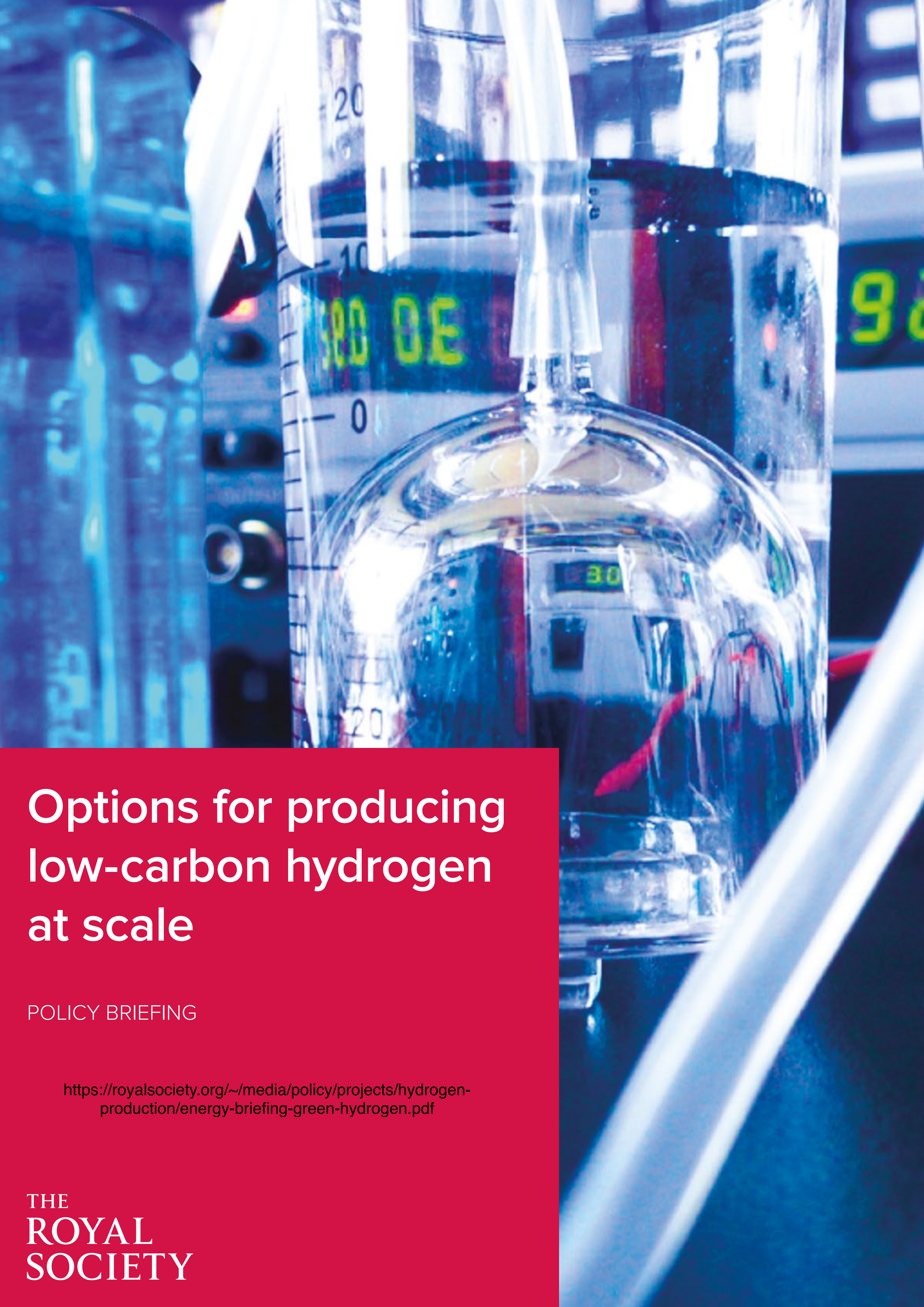

# Options for producing low-carbon hydrogen at scale

POLICY BRIEFING

https://royalsociety.org/~/media/policy/projects/hydrogen-production/energy-briefing-green-hydrogen.pdf

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## POLICY BRIEFING

Politics and science frequently move on vastly different timescales. A policymaker seeking evidence on a new policy will often need the answer in weeks or months, while it takes years to design and undertake the research to rigorously address a new policy question. The value of an extended investigation into a topic cannot be understated, but when this is not possible good evidence is better than none.

The Royal Society's series of policy briefings is a new mechanism aiming to bridge that divide. Drawing on the expertise of Fellows of the Royal Society and the wider scientific community, these policy briefings provide rapid and authoritative syntheses of current evidence. These briefings lay out the current state of knowledge and the questions that remain to be answered around a policy question often defined alongside a partner.

***Options for producing low-carbon***
***hydrogen at scale***
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**royalsociety.org/low-carbon-energy-programme**

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**Cover image:** © science photo / Shutterstock

# Contents

# Executive summary

Hydrogen has the potential to play a significant role in tackling climate change and poor air quality. It is not a cure all and should be seen as one of the possible pathways to a low carbon energy future. There are barriers to the realisation of a hydrogen-based economy including: production at scale, infrastructure investments, bulk storage, distribution and safety considerations. There is also the issue of how to create a simultaneous demand and supply for hydrogen technologies. This report sets out the best available evidence as to how hydrogen could be produced at a scale useful to power vehicles, heat homes and be used by industry. In doing so it aims to inform those making decisions in areas such as research and innovation funding and the provision of physical infrastructure. By framing the uncertainties around the future uses of hydrogen, it also aims to inform wider discussion on pathways to a low carbon economy

The briefing gives an indication of the production technologies, the readiness of each technology, the scale of cost for each and provides insights on the likely source of hydrogen at scale in coming decades.

Four groups of hydrogen production technologies are examined here in order of technology readiness.

The first group of technologies has at its heart a process known as steam methane reforming, which has been used to produce hydrogen from fossil fuels for decades. The process uses natural gas and steam to produce hydrogen. The technology is well understood and is operated on an industrial scale around the world. Carbon capture and storage will be essential if this method is to be used to produce low-carbon hydrogen. Emerging thermal methods include microwaving hydrocarbons and the conversion of fossil fuels in the ground to avoid carbon dioxide emissions. Biomass gasification with carbon capture also provides a possible route to reduced carbon emissions.

Electrolysis comprises the second group of technologies. This process separates hydrogen from water using electricity in an electrolysis cell. Electrolysis produces pure hydrogen which is ideal for fuel cell electric vehicles. It has a high efficiency though many current facilities are small. This technology shows great potential to be scaled up and used as a way of converting excess electrical energy produced by renewables into hydrogen, which enables energy storage flexibility. Economic viability relies in part on the availability of sources of low carbon, low cost electricity.

The third group is biological methods whose key features are lower operating temperatures and relatively simple technology. These primarily relate to a variation of anaerobic digestion that uses microbes to convert biomass to hydrogen instead of methane, together with emerging biotechnologies that allow a greater hydrogen yield from the original biomass. These microbial processes are being developed at both laboratory scale and at demonstration level and have potential to make a small but valuable contribution to the hydrogen economy. In addition, current research indicates that there is scope for these technologies to play an important role in the production of high value chemicals

The final group of technologies is known as solar to fuels. This technology harnesses sunlight to split water into hydrogen and oxygen and has been referred to as 'artificial photosynthesis'. Solar to fuels is an active area of scientific innovation, with potential to lead to a disruptive future process; however it is currently a subject of basic research with elements undergoing technological development. There are no current estimates for potential output and questions over ultimate cost and efficiency.

This briefing challenges the established view that steam methane reforming is the only solution to producing hydrogen at scale for the next 30 years. The science presented here, tells a different story. Electrolysis has the potential to be deployed to produce low-carbon hydrogen in the near to mid-term alongside steam methane reforming, provided the challenges above are met.

# Why hydrogen?

Hydrogen is the most abundant element in the Universe. On Earth, it is found in many chemical compounds, but as a gas it rarely occurs naturally. When generated as a gas it can be used as an energy carrier, which at the point of use produces no carbon dioxide. The large-scale production of low-carbon hydrogen has the potential to play a significant role in tackling climate change and improving air quality. This has two aspects. Firstly, hydrogen is currently used in many industrial processes, and hydrogen production results in the emission of carbon dioxide. Producing hydrogen using low-carbon methods therefore has the potential to reduce those emissions. Secondly, using hydrogen as a fuel produces no carbon dioxide, and it can be used flexibly to power transport and decarbonise multiple parts of the energy system including heating buildings. The conversion of the natural gas network to hydrogen and the use of hydrogen in fuel cell electric vehicles could play an important role in reducing overall greenhouse gas emissions and air pollutants. The UK Government's Clean Growth Strategy illustrates a potential hydrogen demand of roughly 700 TWh by 2050[1] (see annex A for units explanation).

There are significant challenges to a hydrogen-based economy including: large-scale capital investments in plant, bulk storage and distribution, safety and security considerations as well as the issue of how to stimulate both demand and supply for hydrogen technologies[2]. Producing hydrogen is energy intensive for most methods of production. Converting between energy states during the production of hydrogen, incurs an efficiency penalty. The more energy conversions that take place between the prime energy source and the final use, the lower the overall system efficiency will be. To overcome these challenges and realise the potential benefits that hydrogen can bring, a holistic consideration of the hydrogen supply chain is needed.

This paper focuses on arguably the most challenging barrier to the hydrogen economy – producing hydrogen at a range of scales with little or no carbon emissions at acceptable cost. To achieve this, existing technologies need to be decarbonised and new technologies need to be developed (see figure 1).

## 1.1 Additional considerations for deployment

The safe, efficient, effective supply and affordable storage of hydrogen are the main technical challenges associated with the uptake of hydrogen in the energy system.

The decision to co-locate the production, storage and end use of hydrogen will be dependent on the technology used. Centralised and decentralised production infrastructure will bring different challenges. Off-grid deployment will tend towards the use of renewables with production facilities on-site, whilst some large urban areas might need large scale hydrogen infrastructure to produce, transport and store hydrogen.

Varying quality of hydrogen will be necessary for different uses. For example, some fuel cell types need very pure hydrogen. In these cases, hydrogen will need to be purified at the point of use as it can become contaminated in the pipeline. Additionally, additives may be necessary depending on the circumstances; for example, odorants will be essential to detect leaks.

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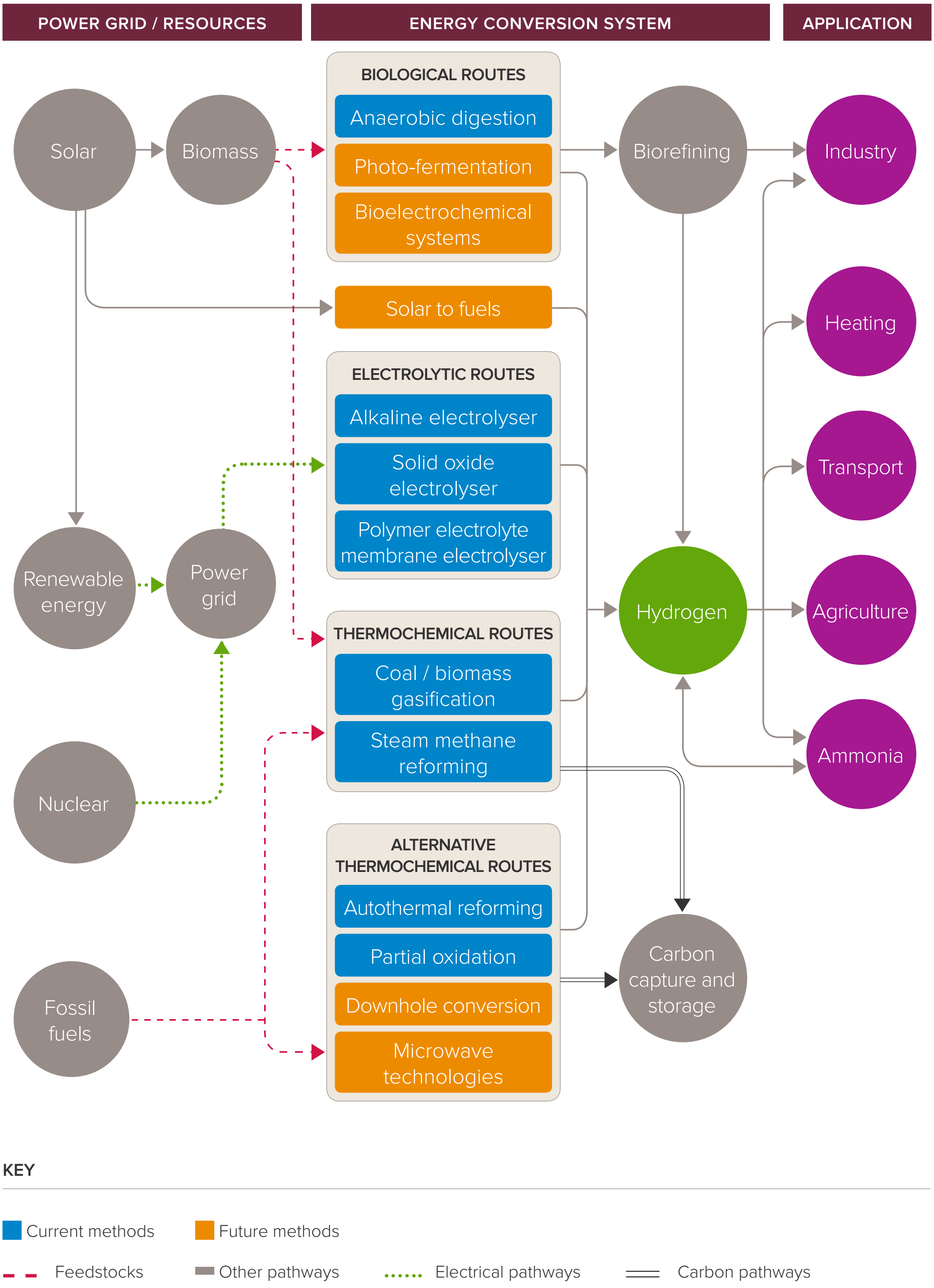
1. HM Government. 2017 The Clean Growth Strategy See: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/651916/BEIS_The_Clean_Growth_online_12.10.17.pdf (accessed 23 November 2017).
2. Brandon N, Kurban Z. 2017 Clean Energy and the Hydrogen Economy. *Phil. Trans. R. Soc. A* **375**: 20160400. (doi:10.1098/rsta.2016.0400).

FIGURE 1

Potential components of the low-carbon hydrogen system



Storing hydrogen for example in cars, requires high pressure tanks which present their own risks. The pressurisation is energy intensive and capacity is ultimately limited. For very large-scale storage of hydrogen (TWh scale) the most viable option is likely to be in geological formations such as salt caverns or depleted fossil fuel reservoirs. Salt caverns have been used to store hydrogen in the UK but the economic and practical feasibility of each facility will need to be considered in further detail[3].

An alternative way of transporting and storing hydrogen is to use ammonia (see case study 1). The Royal Society is exploring further the science of ammonia as an energy storage system.

Options to decarbonise existing industrial processes include the use of low-carbon hydrogen in novel synthetic pathways, storing hydrogen from renewables to generate electricity at a later date and the use of hydrogen as a heat source. For example, on Teesside ethylene production is being effectively decarbonised by the use of ethane as a feedstock. This process generates hydrogen as a by-product, which then is used as an energy source, displacing natural gas and reducing carbon emissions.

> The Royal Society is exploring further the science of ammonia as an energy storage system.

**CASE STUDY 1**

## Ammonia – a resource of growing interest

Over 50% of the current worldwide production of hydrogen is used in the synthesis of ammonia, which, in turn, is principally used to make fertilisers. Hydrogen from steam methane reforming is reacted with nitrogen to form ammonia using the Haber-Bosch process. This is a highly optimised, energy-intensive industrial process that requires about 27 GJ of energy per tonne of ammonia. Worldwide production of ammonia stands at about 170 million tonnes per year. Ammonia synthesis is responsible for approximately 2% of annual global carbon dioxide emissions. Production of low-carbon hydrogen will significantly reduce the greenhouse gas emissions associated with fertiliser production.

As well as a fertiliser, ammonia can be considered as a promising long-term hydrogen transport and storage option (see figure 2). It is relatively safe and stable but its decomposition leads to the evolution of hydrogen and nitrogen. Ammonia has 40% of the calorific value of hydrocarbon fuels and its complete combustion produces nitrogen and water.

In energy storage terms, the annual ammonia production of CF Fertilisers UK Ltd on Teesside is equivalent to more than 10 Tesla Gigafactories and similar in magnitude to the projected hydrogen energy content of the H21 Leeds City Gate project (see case study 2).

Ammonia is a versatile fuel that can be used directly in high-temperature solid oxide fuel cells, cracked for low-temperature fuel cells, and partially cracked for combustion in turbines and internal combustion engines.

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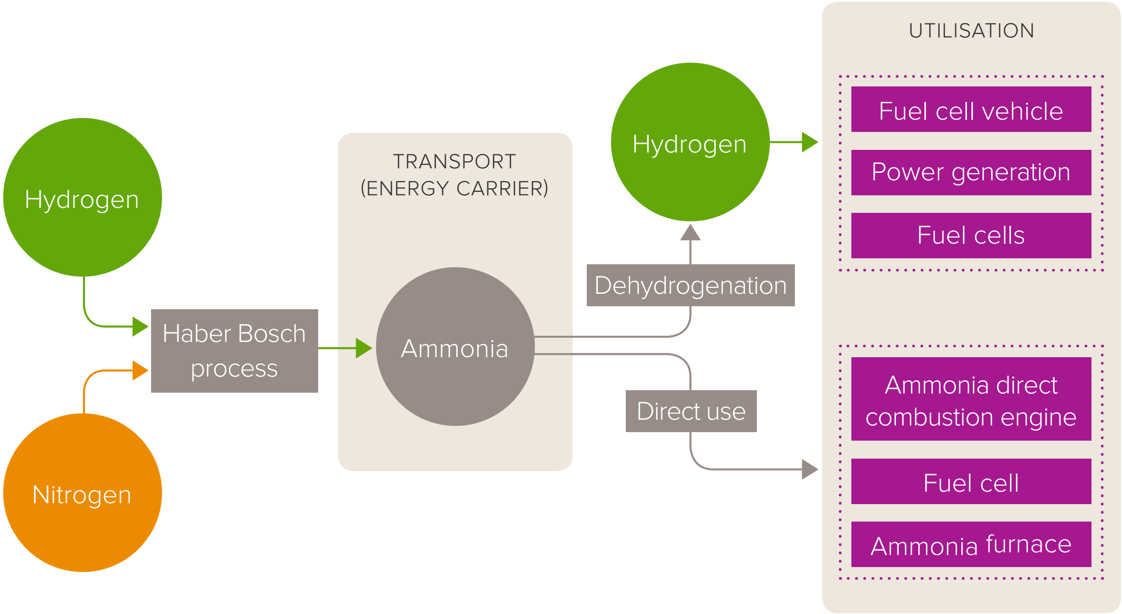
3. Brandon N, Kurban Z. 2017 Clean Energy and the Hydrogen Economy. *Phil. Trans. R. Soc. A* **375**: 20160400. (doi:10.1098/rsta.2016.0400).

**FIGURE 2**

Ammonia as an energy carrier



# Thermochemical routes to hydrogen

95%
of the global production of hydrogen is generated from fossil fuels.

Hydrogen has been commercially produced using fossil fuels for decades[4]. Until the late 1960's, domestic town gas was the prevailing gas supply in the UK, containing roughly 50% hydrogen[5].

Currently, around 95% of the global production of hydrogen is generated from fossil fuels, primarily from natural gas with steam methane reforming and coal gasification[6] (see figure 3). UK production of hydrogen follows this trend with the majority of the total produced (26.9 TWh/year[7]) coming from steam methane reforming. Coal gasification is likely to continue to make a small contribution and biomass gasification has potential on a small scale.

All of these thermochemical methods emit carbon dioxide either from the energy input or as a by-product. Carbon capture and storage is therefore an essential prerequisite if any of these methods are to play any part in a low-carbon hydrogen economy.

## Steam methane reforming

Steam methane reforming involves reacting natural gas with steam at high temperatures over a catalyst to produce syngas (a mixture of hydrogen and carbon monoxide) which is then further processed to separate the hydrogen.

Production capacities of hydrogen from a typical steam methane reforming plant range between 150 and 440 MW[8] with an energy efficiency of typically 70%[9]. If steam methane reforming is to become a major low-carbon source of hydrogen, carbon capture and storage is essential. The approximate technology readiness level of steam methane reforming with carbon capture and storage is 8. Efficiency improvements will be highly desirable, as the addition of carbon capture and storage will result in a reduction in overall production efficiency by 5 – 14%[10, 11].

It is estimated that between 71% and 92% of the carbon in steam methane reforming can be captured[12, 13], however higher capture rates will be needed if the process is to be used in the long term. The Leeds H21 feasibility study (see heat case study) highlights the importance meeting urban area hydrogen demand with the use of carbon capture and storage with steam methane reforming.

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[4] E4 Tech, University College London Energy Institute, Kiwa Gastec. 2015 Scenarios for Deployment of Hydrogen in Contributing to Meeting Carbon Budgets and the 2050 Target. See https://www.theccc.org.uk/wp-content/uploads/2015/11/E4tech-for-CCC-Scenarios-for-deployment-ofhydrogen-in-contributing-to-meeting-carbon-budgets.pdf (accessed 16 November 2017).

[5] Energy Research Partnership. 2016 Potential Role of Hydrogen in the UK Energy System. See http://erpuk.org/wpcontent/uploads/2016/10/ERP-Hydrogen-report-Oct-2016.pdf (accessed 16 November 2017).

[6] OECD/IEA. 2017 Renewable Energy for Industry. See: https://www.iea.org/publications/insights/insightpublications/Renewable_Energy_for_Industry.pdf (accessed 16 November 2017).

[7] Energy Research Partnership. 2016 Potential Role of Hydrogen in the UK Energy System. See http://erpuk.org/wpcontent/uploads/2016/10/ERP-Hydrogen-report-Oct-2016.pdf (accessed 16 November 2017).

[8] Northern Gas Networks. 2016 Leeds City Gate H21. See https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf (accessed 16 November 2017).

[9] Sustainable Gas Institute, Imperial College London. 2017 A Greener Gas Grid: What are the Options? White Paper. See http://www.sustainablegasinstitute.org/a-greener-gas-grid/ (accessed 16 November 2017).

[10] Jansen D, Gazzani M, Manzolini G, van Dijk E, Carbo M. 2015 Pre-combustion $CO_2$ capture. International Journal of Greenhouse Gas Control, **40**: 167-187. (doi.org/10.1016/j.ijggc.2015.05.028).

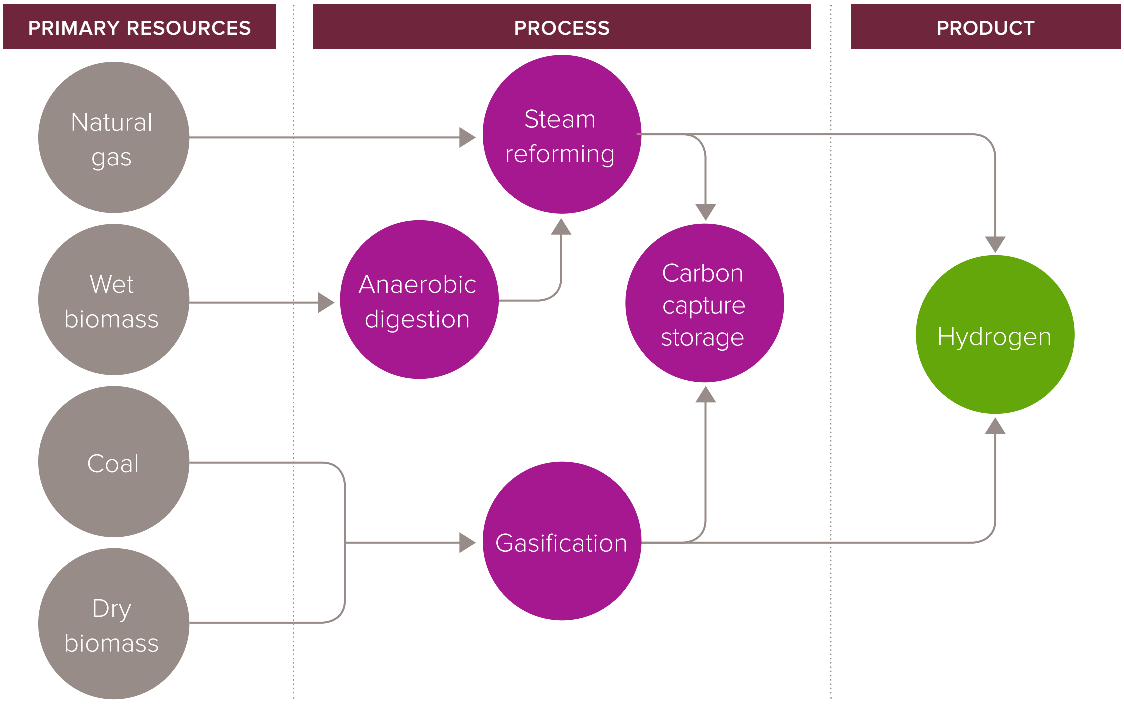
[11] Rubin E, Mantripragada H, Marks A, Versteeg P, Kitchin J. 2012 The outlook for improved carbon capture technology. Progress in Energy and Combustion Science, **38**: 630-671. (doi.org/10.1016/j.pecs.2012.03.003).

[12] Ruether, J., M. Ramezan, and E. Grol, Life-Cycle Analysis of Greenhouse Gas Emissions for Hydrogen Fuel Production in the United States from LNG and Coal U. Department of Energy, Editor. 2005, National Energy Technology Laboratory

[13] Northern Gas Networks. 2016 Leeds City Gate H21. See https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf (accessed 16 November 2017).

**FIGURE 3**

Thermochemical routes to hydrogen



Adapted from Sustainable Gas Institute report, 2017[14].

**CASE STUDY 2**

## Hydrogen for heat – Leeds H21

The *H21 Leeds City Gate* report[i] identified the system requirements (at feasibility level) to convert one city in the UK to 100% hydrogen. The report concluded that it would be possible to reuse the city's existing gas grid and low-carbon hydrogen could be credibly provided along the following design parameters:

- Hydrogen would be provided through a production capacity of 1,025 MW via four 256 MW Steam Methane Reformers located at Teesside due to its access to industrial heritage, hydrogen storage and potential carbon capture and storage facilities.
- Intraday storage of circa 4,000 MWh is provided via salt caverns in the Teesside region
- Inter-seasonal storage of 700,000 MWh is provided via salt caverns in the Humber region
- 1.5m tonnes of carbon dioxide would be sequestered per annum.

[i] Northern Gas Networks. 2016 Leeds City Gate H21. See https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf (accessed 16 November 2017).

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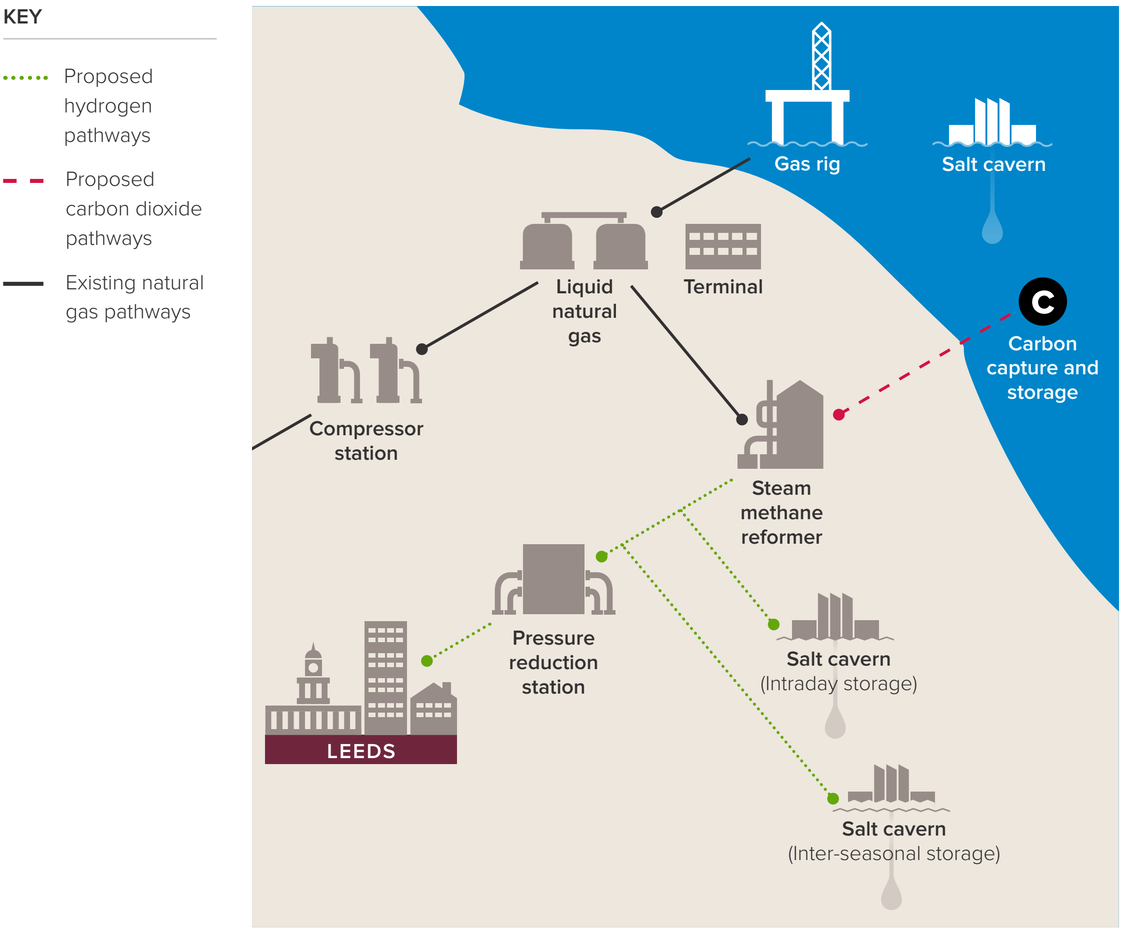
14. Sustainable Gas Institute, Imperial College London. 2017 A Greener Gas Grid: What are the Options? White Paper. See http://www.sustainablegasinstitute.org/a-greener-gas-grid/ (accessed 16 November 2017).

FIGURE 4

Leeds H21 feasibility study map of proposed infrastructure.

The H21 Leeds City Gate report suggested that the UK gas grid could be converted to 100% hydrogen. Considerable work is required to prove this concept but conversion of UK cities could be achieved incrementally up to 2050 and that appliances could be converted to operate on 100% hydrogen. The H21 project also concluded that a conversion to 100% hydrogen in the UK gas grid could represent a credible and deliverable industrial strategy to meet UK and global climate change obligations, allowing the UK to meet its clean energy targets by 2050. H21 Studies are now under development in Australia and Ireland, and interest is being shown in China, Japan, Hong Kong, New Zealand and across Europe.



Adapted from Leeds City Gate H21 report Northern Gas Networks. 2016 Leeds City Gate H21. See https://www.northerngasnetworks.co.uk/wp-content/uploads/2017/04/H21-Report-Interactive-PDF-July-2016.compressed.pdf (accessed 16 November 2017).

### Coal gasification

Coal gasification is the process that produced ‘town gas’ in the UK. Due to the high carbon content of coal and the energy intensity of this process, coal gasification is unlikely to be useful into the future (see table 1 in Section 6.2). It is a mature technology but has variable capital investment costs and a low energy efficiency[15]. Pilot coal plants with carbon capture and storage for electricity generation have been demonstrated but not at commercial scale. Coal gasification efficiencies would be further reduced by the necessary use of carbon capture and storage.

### Biomass gasification

Biomass such as wood, straw or waste can also be used in gasification[16]. The process is similar to that of using coal but the need for pre-treatment adds complexity and cost. Demonstrators have been constructed at a pilot scale, with a 50 kW plant built in the UK with plans to build a commercial plant capable of 45 MW under development[17]. Biomass gasification when coupled with carbon capture and storage could lead to hydrogen production with no or negative carbon emissions but this depends on the overall energy balance and has not yet been demonstrated.

## 2.1 Alternative thermochemical processes for hydrogen production

### Autothermal reforming and partial oxidation

Autothermal reforming and partial oxidation can also be used to produce syngas from the same range of feedstocks. These approaches use oxygen to generate the heat required through partial combustion of the feedstock. These processes can operate at smaller scales and both approaches have similar efficiencies as steam methane reforming.

### Pyrolysis of hydrocarbons.

It is possible to decompose hydrocarbons such as methane in a process known as pyrolysis, to produce solid carbon and hydrogen gas. The process involves heating the hydrocarbon to a high temperature in the absence of oxygen. The solid carbon could, once isolated and collected, be sequestered. The technology to do this is at a very early research stage[18].

### Downhole conversion of fossil fuels to hydrogen with carbon dioxide sequestration

Underground coal gasification was originally developed as a method of producing hydrogen and syngas from un-mined coal resources through the underground combustion of coal in the presence of water. The process fell out of favour due to the low calorific value of the gas mixture compared to natural gas and environmental concerns. To be used in conventional fossil fuel reservoirs, carbon capture and storage would be needed post recovery, however, shale gas reservoirs offer the potential for hydrogen generation and release, coupled with carbon dioxide adsorption[19,20].

Shale gas reservoirs offer the potential for hydrogen generation and release.

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15. E4 Tech, University College London Energy Institute, Kiwa Gastec. 2015 Scenarios for Deployment of Hydrogen in Contributing to Meeting Carbon Budgets and the 2050 Target. See https://www.theccc.org.uk/wp-content/uploads/2015/11/E4tech-for-CCC-Scenarios-for-deployment-ofhydrogen-in-contributing-to-meeting-carbon-budgets.pdf (accessed 16 November 2017).
16. Sikarwar V, Zhao M, Clough P, Yao J, Zhong X, Memon M, Shah N, Anthony E, Fennell P. 2016 An overview of advances in biomass gasification. *Energy & Environmental Science*, **9**: 2939-2977 (doi:10.1039/C6EE00935B)
17. Cadent Gas Lt, Advanced Plasma Power, Progressive Energy. 2017 Biohydrogen: Production of hydrogen by gasification of waste. See http://gogreengas.com/wp-content/uploads/2015/11/Biohydrogen-Cadent-Project-Report-FINAL-3.pdf (accessed 16 November 2017).
18. Weger L, Abánades A, Butler T 2016 Methane cracking as a bridge technology to the hydrogen economy *International Journal of Hydrogen Energy* Volume 42, Issue 1, 5 January 2017, (DOI/10.1016/j.ijhydene.2016.11.029
19. Heller R, Zoback M. 2014 Adsorption of methane and carbon dioxide on gas shale and pure mineral samples, *Journal of Unconventional Oil and Gas Resources* 8, 14-24. (DOI:org/10.1016/j.juogr.2014.06.001).
20. Ghosh S. et al. 2016, Defining a performance map of porous carbon sorbents for high-pressure carbon dioxide uptake and carbon dioxidemethane selectivity, J. Mater. Chem. A **4**, 14739-14751. (DOI: 10.1039/C6TA04936B).

The UK has world-leading industrial and academic activities in membranes.

Further studies are required into the reaction engineering and process under downhole conditions, as well as a detailed analysis of the economic and environmental considerations.

### Microwave technologies

New microwave techniques with bespoke catalysts have been shown to release large amounts of pure (greater than 98%) hydrogen from hydrocarbons such as diesel and wax. Unwanted by-products such as carbon dioxide and methane are suppressed, leaving only solid carbon. This point-of-use hydrogen generation, using cheap, earth-abundant catalysts such as iron or nickel could utilise the existing petrochemical transport and storage infrastructures[21,22]. This technique is at low technology readiness level. A source of low carbon electricity will be required.

## 2.2 Thermochemical challenges and research needs

The critical challenge to the use of thermochemical production is the availability of carbon capture and storage to decarbonise the process. Catalysts are also important in this process as they reduce the energy required in a reaction. The UK has world leading catalytic scientists and companies, for example Johnson Matthey plc make catalysts and John Wood plc build steam methane reformers.

### Use of membranes

The incorporation of membranes that can selectively remove hydrogen and/or carbon dioxide can significantly enhance thermochemical routes for low-carbon hydrogen production. Work is needed to improve the function and stability of the membrane and in particular to integrate membranes into the various chemical processes. These offer the prospect of enabling hydrogen production over a wider range of scales, at lower cost, and with increased efficiency. Such membranes are already under development, but greater focus and effort is needed to explore a wider range of materials, and to explore membrane integration within the production process.

The UK has world-leading industrial and academic activities in membranes. The Engineering and Physical Science Research Council has a grants programme that brings together five UK universities with eleven companies to work on membrane technologies[23]. Further afield, Tokyo Gas has used a 20 micron thick palladium membrane to produce high purity hydrogen from syngas.

### Solid-looping cycles for carbon capture and storage

An approach to carbon capture and storage that may be appropriate for thermochemical processes is known as solid looping. In a specific example using calcium oxide, the carbon dioxide-containing stream is passed over a bed of calcium oxide, which reacts with the carbon dioxide and forms calcium carbonate. The solid calcium carbonate is transported to a second reactor where the carbon dioxide is driven off in a concentrated stream that can be recovered and stored, while the calcium oxide is recovered for re-use in the process. Process integration will increase efficiency.

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21. Jie X, Gonzalez-Cortes S, Xiao T, Wang J, Yao B, Slocombe D, Al-Megren H, Dilworth J, Thomas J, Edwards P. 2017 Rapid production of high-purity hydrogen fuel through microwave-promoted deep catalytic dehydrogenation of liquid alkanes with abundant metals. *Angewandte Chemie – International Edition*, **56**: 10170-10173. (doi:10.1002/anie.201703489).
22. Gonzalez-Cortes S, Slocombe D, Xiao T, Aldawsari A, Yao B, Kuznetsov V, Liberti E, Kirkland A, Alkinani M, Al-Megren H, Thomas J. 2016. Wax: A benign hydrogen-storage material that rapidly releases H2-rich gases through microwave-assisted catalytic decomposition. *Scientific Reports*, **6**: 35315. (doi:10.1038/srep35315).
23. EPSRC (Engineering and Physical Sciences Research Council). 2017 From membrane material synthesis to fabrication and function (SynFabFun). See http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/M01486X/1 (accessed 16 November 2017).

### Solid-looping cycles for hydrogen production

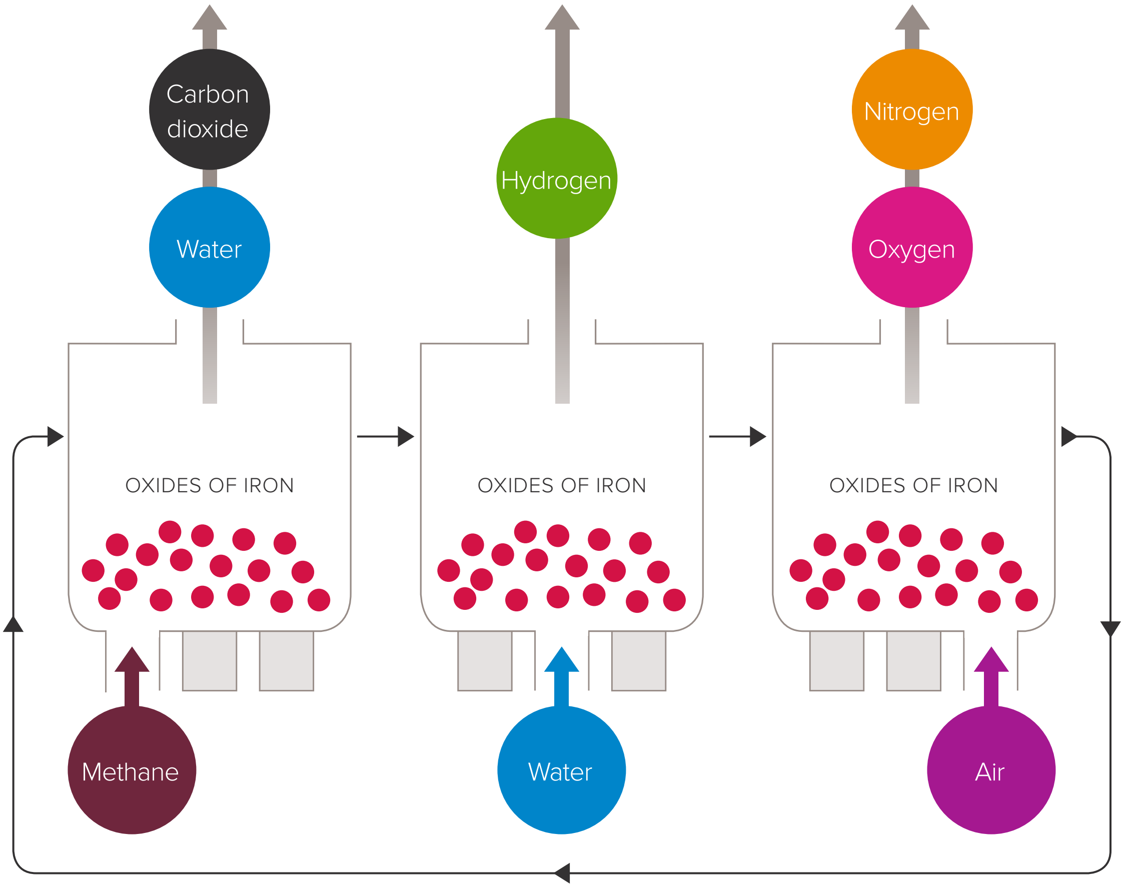
Solid-looping cycles (sometimes known as chemical-looping) for the production of hydrogen are at a low technology readiness level, but present opportunities for reducing carbon footprints as they have inherent thermodynamic advantages. There are outstanding issues such as materials stability which need to be overcome. However, solid-looping cycles should be considered as important platform technologies that need further development (see figure 5).

Solid-looping cycles are a European strength with a number of large pilot plants located on the Continent. The International Energy Agency Greenhouse Gas Research and Development Programme runs a network covering this subject. There is UK academic activity in a number of institutions including Newcastle University, Cranfield University, Imperial College London, University of Leeds and the University of Cambridge.

**FIGURE 5**

Chemical looping cycle example

A three-stage process can be performed in a chemical looping process. The cycle uses iron as a carrier in a series of oxidation and reduction reactions with methane, water and air in turn to produce carbon dioxide and water, hydrogen and nitrogen gases. The iron is not lost and remains in the reaction cycle.



# Electrolytic routes to hydrogen

The carbon footprint of hydrogen from electrolysis will be dependent on the source of power used.

Electrolytic hydrogen production, also known as electrolysis, splits water into hydrogen and oxygen using electricity in an electrolysis cell, as seen in figure 6. Electrolysis produces pure hydrogen which is ideal for low temperature fuel cells for example in electric vehicles (see case study 3 for end uses of hydrogen in transport).

There is a range of different electrolyser technologies. Alkaline electrolysers are the most technically mature, with the largest current plant being up to 2.5 MW capacity[24]. However, alkaline electrolysers do not work well with intermittent renewable energy sources. The world's largest alkaline electrolyser plant was 135 MW and was operated by Norsk Hydro in Glomfjord, Norway from 1953 to 1991 until it became uneconomic against the low cost of natural gas.

Polymer electrolyte membrane electrolysers are developing quickly. Siemens has been operating a 6 MW electrolyser in Mainz since 2015. ITM Power Ltd has secured a joint venture project with Shell to construct a 10 MW electrolyser in the Rhineland Refinery Complex in Germany[25].

Solid oxide electrolysers are less technically mature but potentially offer the highest efficiency of all the electrolyser options if they can be coupled to a suitable source of zero carbon heat.

Efficiencies for electrolysers are improving steadily. Process efficiencies of 85% to 95% are expected to be possible in the near future for both small and medium-sized electrolysers[26]. The lifespan of an electrolyser is dependent on hydrogen production rates with some research indicating a trade-off between rate and longevity due to the gradual degradation of the polymer electrolyser membranes. The efficiency of all electrochemical technologies is largely independent of scale, which supports the use of smaller devices for distributed hydrogen production[27].

Ultimately, the carbon footprint of hydrogen from electrolysis will be dependent on the source of power used. Carbon emissions will be lower if the source of electricity is low carbon.

## 3.1 Electrolysis challenges and research needs

For all electrolysers, there is a requirement to fulfil a number of different goals:

- High efficiency and hydrogen production rate
- Long life span
- Low capital cost
- Provide grid balancing for renewable generation
- Compactness

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[24] Sustainable Gas Institute, Imperial College London. 2017 A Greener Gas Grid: What are the Options? White Paper. See http://www.sustainablegasinstitute.org/a-greener-gas-grid/ (accessed 16 November 2017).

[25] ITM-Power. 2017 10MW Refinery Hydrogen Project with Shell. See http://www.itm-power.com/news-item/10mw-refinery-hydrogen-project-withshell, (accessed 16 November 2017).

[26] Dodds P & McDowall W. 2012 A review of hydrogen production technologies for energy system models. See http://www.wholesem.ac.uk/bartlett/energy/research/themes/energy-systems/hydrogen/WP6_Dodds_Production.pdf (accessed 16 November 2017).

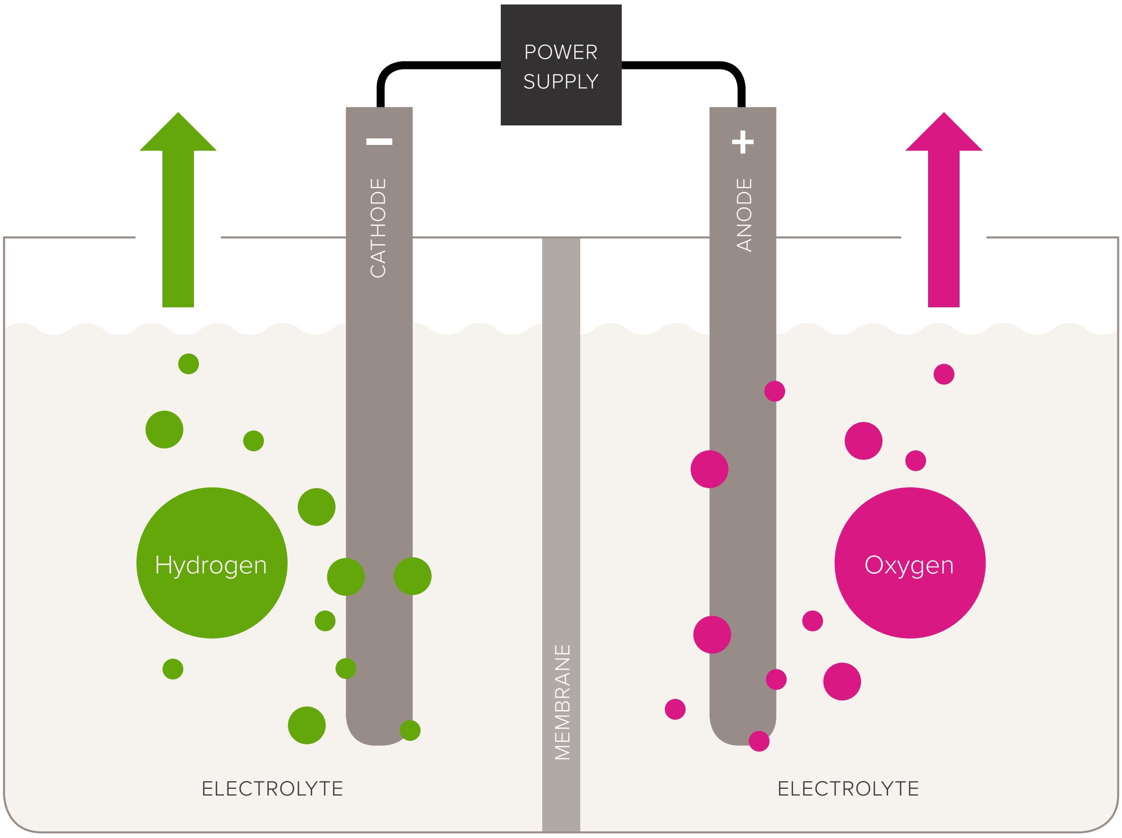
[27] Ursua A, Gandia L, Sanchis P. 2012 Hydrogen Production From Water Electrolysis: Current Status and Future Trends. *Proceedings of the IEEE*, **100**: 410-426. (doi:10.1109/JPROC.2011.2156750).

All electrolysers face common scientific and engineering challenges. In the near term, developing better electrodes and new catalysts will lead to decreased costs as the same amount of hydrogen will be produced from smaller reactors. This will be helped by better system integration and production of a supply chain to provide the specialist components used in electrolysers. Over the longer term, improvements in electrolytes, better understanding of mechanisms and the introduction of high temperature electrolyser systems will increase efficiency and lead to a further drop in hydrogen costs. Such improvements over time will support the off-grid deployment of electrolysis with renewables.

The UK's key strengths in this research area lie in fundamental electrochemistry as well as materials design and modelling of electrochemical systems. In particular, the UK is internationally recognised in terms of electrochemical diagnostics and systems optimisation. Companies such as ITM Power and Johnson Matthey also have expertise in polymer electrolyte membrane electrolysis.

**FIGURE 6**

The production of hydrogen and oxygen through electrolysis



CASE STUDY 3

## Hydrogen for transport

After decades of research and development the hydrogen transport sector is now making a transition from discrete demonstrations to become an emerging commercial activity. Global automotive companies such as Honda, Toyota and Hyundai back the deployment of hydrogen passenger cars in the UK. However, this sector also features UK based small-medium enterprises such as Microcab and Riversimple – their small, lightweight fuel cell road vehicles are progressing towards market entry. Other hydrogen vehicle sectors show early promise in the UK, notably hydrogen buses (for example Wright and Alexander Dennis) and light vans (for example Ulemco and Arcola Energy). The emergence of viable hydrogen passenger trains, such as the Alstom Coradia iLint[i] provide a significant opportunity for the replacement of diesel train services, without the cost and disruption of electrification of lines.

Successful implementation of hydrogen road vehicles depends on the installation of an adequate number of refuelling stations. The UK H2Mobility project[ii], a partnership between government and industry set out a development plan for hydrogen refuelling stations in the UK and has been financially supported by UK Government and European grant programmes for fuelling station installation and vehicle deployment.

One of the most prominent examples of low-carbon hydrogen transport development in the UK is in Aberdeen. The Aberdeen Hydrogen Bus Project enabled the deployment of Europe's largest fleet of 10 hydrogen buses, together with a small number of hydrogen light vans and Hyundai fuel cell passenger vehicles. The £19m project cost was met through a combined investment from European, UK, Scottish Government and the City council as well as industrial funding. This initial station produces up to 400kg hydrogen per day on site via a 1MW alkaline electrolyser.

i. Alstom. 2017 Coradia iLint regional train. See: http://www.alstom.com/products-services/product-catalogue/rail-systems/trains/products/coradia-ilint-regional-train-/ (accessed: 24 November 2017)

ii. UK H2 Mobility. 2017 See: http://www.ukh2mobility.co.uk/ (accessed: 24 November 2017)

# Biological routes to hydrogen

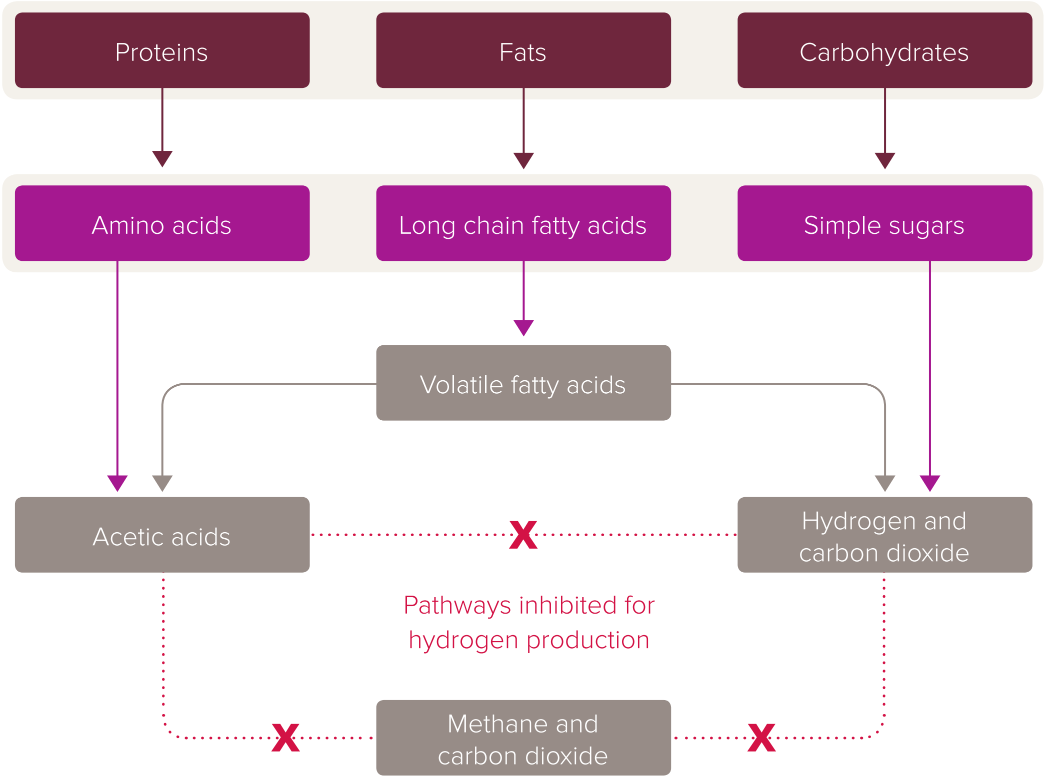
Microbial processes can convert biomass to hydrogen and other valuable end products. Typically, biomass is broken down by microorganisms in the absence of oxygen to produce hydrogen in a process known as anaerobic digestion. Microbial processes have a number of advantages over other hydrogen production technologies such as lower operating temperatures, a simpler technological basis and the ability to be used with a wide range of wet and dry biomass types, such as straw and sewage.

Anaerobic digestion is used for the production of energy from wet biomass and has been used successfully to produce methane from waste biomass for many decades. This technology is can be adjusted to produce hydrogen.

As Figure 7 shows, the production of hydrogen via anaerobic digestion is a part of the established methane process. In a fermenter producing methane, the hydrogen produced by one group of organisms is converted to methane by a second group. In a hydrogen producing fermenter, the second group of organisms are selectively inhibited by changing the conditions, such as pH and temperature to prevent the conversion of hydrogen to methane.

**FIGURE 7**

Anaerobic digestion pathways to hydrogen instead of methane.



> Biological methods have the potential to make a small but valuable contribution to the hydrogen economy.

## 4.1 Alternative methods for microbial conversion of biomass to hydrogen

More recently, technologies have arisen to produce additional hydrogen from by-products of fermentation[28]. Examples include the conversion of organic acids to hydrogen using photo-fermentation or microbial electrolysis with the aid of a small amount of electricity[29,30]. These second stage technologies aim to maximize the energy yield from biomass. To achieve the best possible energy yield, it is best used as a part of an integrated biorefining system for hydrogen production from biomass.

The integration of different biological conversion methods to optimize yields, and the development of valuable products in addition to hydrogen underlines a key characteristic and strength of biological conversion – it is a highly flexible, integrated and adaptable process. Rather than simply replacing older biological processes, new technologies can augment them in a biorefinery, increasing yields and unlocking new usage scenarios.

Biological methods have the potential to make a small but valuable contribution to the hydrogen economy. In addition, current research indicates that there is scope for these technologies to play an important role in the production of high value chemicals

## 4.2 Biological methods challenges and research needs

Life cycle analysis is important for all hydrogen production methods. When producing hydrogen from biomass via anaerobic digestion there are several challenges to be addressed, notably their low process efficiencies. The challenges can be summarized as follows:

- increasing the availability and range of biomass types;
- improving the biochemical accessibility of the biomass; and
- improving the yield of convertible biomass to hydrogen.

Many of these challenges are interlinked; the first two could be addressed by looking at energy efficient chemical pretreatments and synthetic biology approaches to convert difficult to process biomass such as straw. These approaches would not only increase the range of biomass available but also the availability for the conversion to hydrogen. The other major challenge is to increase the maximum yield of hydrogen. There are a number of promising avenues to achieve this including the integration of physical separation processes to remove product inhibition from the microbes[31, 32], and the use of synthetic biology approaches[33] or bio-electrochemical systems[34].

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28. Eroglu E. Melis A. 2011 Photobiological hydrogen production: Recent advances and state of the art. *Bioresour. Technol*. **102**: 8403–8413. (doi:10.1016/j.biortech.2011.03.026).
29. Guwy A, Dinsdale R, Kim J, Massanet-Nicolau J, Premier G. 2011 Fermentative biohydrogen production systems integration. *Bioresour. Technol*. **102**: 8534–8542. (doi:10.1016/j.biortech.2011.04.051).
30. Logan B, Call D, Cheng S, Hamelers H, Sleutels T, Jeremiasse A, Rozendal R. 2008 Microbial Electrolysis Cells for High Yield Hydrogen Gas Production from Organic Matter. *Environ. Sci. Technol*. **42**: 8630–8640. (doi:10.1021/es801553z).
31. Jones R, Massanet-Nicolau J, Mulder M, Premier G, Dinsdale R, Guwy A. 2017. Increased biohydrogen yields, volatile fatty acid production and substrate utilisation rates via the electrodialysis of a continually fed sucrose fermenter. *Bioresour. Technol*. **229**: 46–52. (doi:10.1016/j.biortech.2017.01.015).
32. Massanet-nicolau J, Jon R, Guwy A, Dinsdale R, Premier G, Mulder M. 2016 Maximising biohydrogen yields via continuous electrochemical hydrogen removal and carbon dioxide scrubbing. *Bioresour. Technol*. **218**: 512–517. (doi:10.1016/j.biortech.2016.06.115).
33. Burgess S, Taha H, Yeoman J, Iamshanova O, Chan K, Boehm M, Behrends V, Bundy J, Bialek W, Murray J, Nixon P, 2016. Identification of the Elusive Pyruvate Reductase of Chlamydomonas reinhardtii Chloroplasts. *Plant and Cell Physiology*. **57**: 82–94 (doi:10.1093/pcp/pcv167).
34. Popov A, Michie I, Kim J, Dinsdale R, Guwy A, Esteves S, Premier G. 2016 Enrichment strategy for enhanced bioelectrochemical hydrogen production and the prevention of methanogenesis. *Int. J. Hydrogen Energy*. **41**: 4120–4131. (doi:10.1016/j.ijhydene.2016.01.014).

There are other challenges associated with bioconversion to hydrogen, for example in the use of photo fermentation to convert organic acids to additional hydrogen. The principle challenge here is separating nitrogen from the biomaterial prior to photo fermentation and some research has been conducted into this[35].

Hydrogen bioconversion processes could also be applied to existing hydrocarbon resources to extract hydrogen and leave the carbon in-situ underground. The biological conversion of oil and coal hydrocarbons to methane gas has been reported and it may be possible through combining engineering and synthetic biology approaches to replace the methane production with hydrogen production. In the medium term, there is a need to demonstrate the viability of these new technologies for producing biological hydrogen on an industrial scale. Pilot scale research and demonstration facilities for hydrogen production need to be designed and built.

Research in the field of biological production of hydrogen has a significant history in Europe with a number of framework projects including Hyvolution and HyTime. The International Energy Agency's Hydrogen Implementing Agreement currently runs a Task 'Biological Hydrogen for Energy and Environment' which is led by University of South Wales[36]. A number of UK universities are active in the field including University of South Wales, University of Birmingham, University of Oxford, Imperial College London and Newcastle University.

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35. Redwood M, Macaskie L. 2006 A two-stage, two-organism process for biohydrogen from glucose. *Int. J. Hydrogen Energy*. **31**: 1514–1521. (doi:10.1016/j.ijhydene.2006.06.018)

36. IEA Hydrogen. 2017 Biological Hydrogen for Energy and Environment. See: http://ieahydrogen.org/Activities/Task-34-A.aspx (accessed 23 November 2017)

# Solar to fuel routes to hydrogen

'Solar to fuels' is a suite of technologies that typically split water into hydrogen and oxygen using solar energy (see figure 8). Solar to fuels methods have close parallels with the process of photosynthesis and are often referred to as 'artificial photosynthesis' processes.

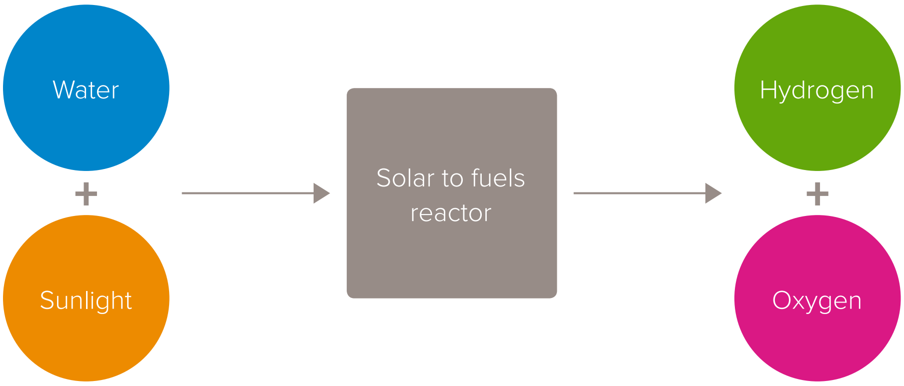
There are many types of solar to fuels technologies, some of which aim to synthesise carbon based fuels such as methane, carbon monoxide and methanol as well as hydrogen (see figure 9). These technologies target the same overall function, and have close synergies with separate photovoltaics and electrolysis routes. The difference is that in 'direct solar to fuels' technologies, fuel production occurs in situ on the device that captures solar energy, without the intermediacy of electricity provided from any renewable source. Such devices are typically based on the nanoscale integration of semiconductors for absorption with catalysts for fuel synthesis. They have lower overall efficiency than photovoltaics plus electrolysis but have the potential to be simpler and cheaper.

Solar to fuels technology is an active area of basic research with potential to lead to disruptive future technologies. The current status is lab scale with a technology readiness level of 1 to 3 but rapid growth could be possible. Major initiatives are ongoing in several countries, including in particular Japan and USA. The global Mission Innovation initiative has identified 'sunlight conversion' (ie solar to fuels) as one of its seven key challenges. This initiative, of which the UK is part, seeks to double governments' clean energy research and development investments over five years, while encouraging greater levels of private sector investment in transformative clean energy technologies[37].

There are no current estimates for potential output and questions over ultimate efficiency and cost.

**FIGURE 8**

The solar to fuels reactor



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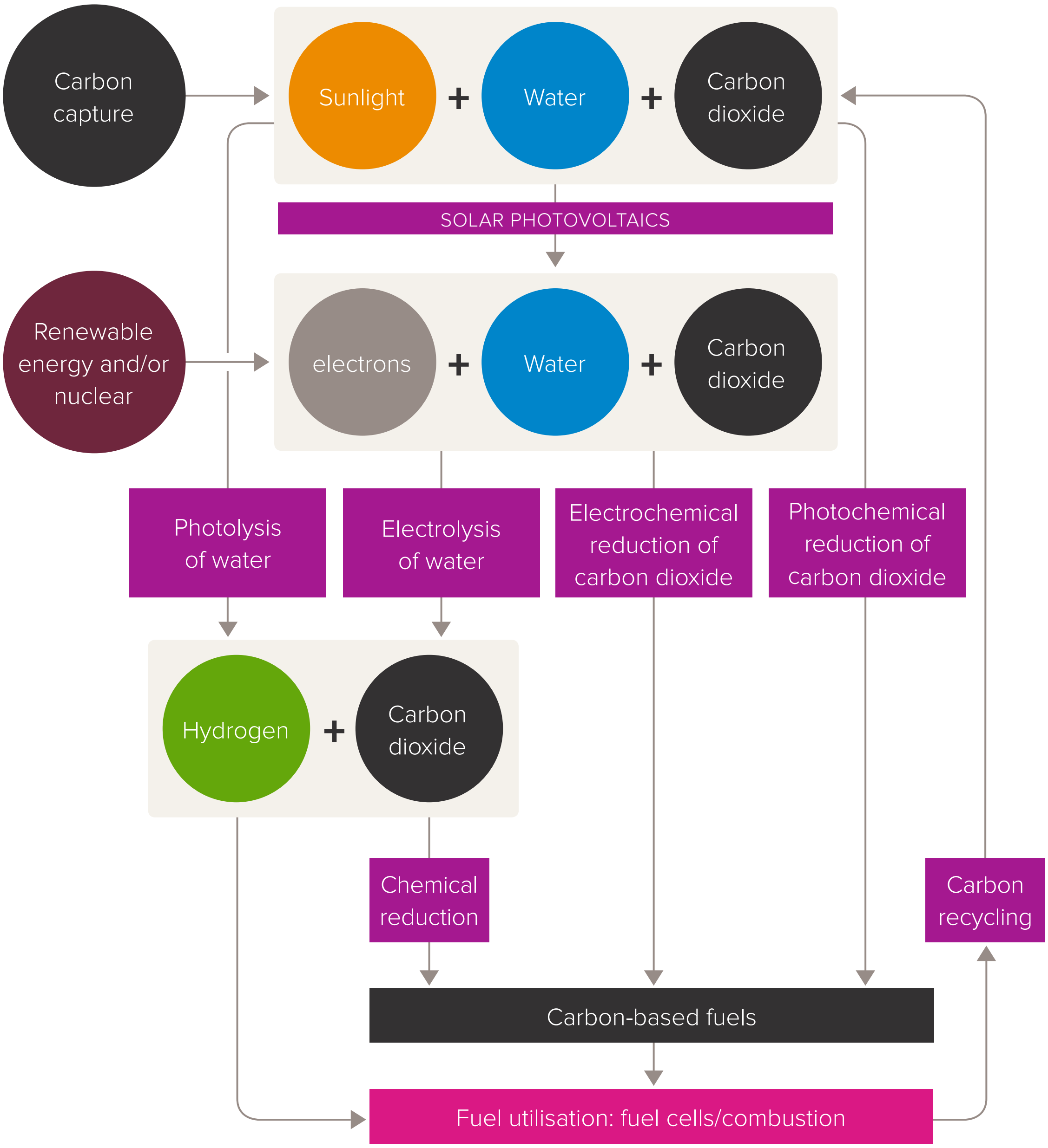
[37] Mission Innovation. 2017 Converting Sunlight Innovation Challenge. See: http://mission-innovation.net/our-work/innovationchallenges/converting-sunlight-challenge/ (accessed 20 November 2017).

**FIGURE 9**

Solar to hydrogen and carbon neutral fuels



A promising but challenging research field is using solar energy to convert carbon dioxide from the atmosphere into liquid fuels.

A wide range of materials and reactor designs are currently being considered for integrated solar to fuels technologies. They range from the deposition of catalysts for fuel synthesis onto photovoltaic devices (often referred to as 'artificial leaves') to photocatalytic nanoparticles suspensions. The former approach currently is the most efficient, but the latter has the greatest potential cost reduction. Light absorbing materials in such reactors range from conventional semiconductors such as silicon to less conventional semiconductors, such as metal oxides, as well as molecular and polymer based materials including carbon nitrides. Such materials are integrated with a range of inorganic and molecular catalysts, typically on the nanoscale, with rapid scientific advances being made in all areas.

### 5.1 Solar to fuels challenges and research needs

Solar to fuels has the potential to be scalable and impact future energy systems, but is not yet typically considered in long term energy system planning, in part due to a lack of demonstrator systems and the difficulty of undertaking reliable cost projections. The technology benefits of solar to fuels will need to be proven against the established combination of photovoltaic and electrolysis technologies. Competition for space with agriculture and other land uses will also remain a challenge to the scale up of solar to fuels.

There is a wide divergence of opinion on which materials and reactor designs are most promising. Photocatalyst sheets may offer the potential for solar driven hydrogen synthesis at costs substantially lower than current PV and electrolysis routes and are already attracting commercial investment.

Development of improved catalysts and light absorbers are challenges common to electrolysis, photovoltaics and direct solar to fuels. The specific challenges for direct solar to fuels include materials stability and exploiting synergies arising from light absorber and catalyst integration to enable very low cost, efficient and scalable solar to fuels devices. Catalyst development has parallels with catalyst development for electrolysis, whilst light absorber development has parallels with photovoltaic materials research – with potential synergies in both areas.

A promising but challenging research field is using solar energy to convert carbon dioxide from the atmosphere into liquid fuels. Finding a catalyst that can facilitate the process with high efficiency and selectivity, as well as integrating it into solar conversion devices remain key problems, however some researchers are reporting efficiencies in the laboratory of better than that of plant photosynthesis[38, 39].

The UK has extensive strengths in advanced energy materials, solar photovoltaic materials and catalysis. Some of this is already targeting solar to fuels.

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[38] Bullock J, Srankó D, Towle C, Lum Y, Hettick M, Scott M, Javey A, Ager J. 2017 Efficient solar-driven electrochemical $CO_2$ reduction to hydrocarbons and oxygenates. *Energy & Environmental Science*. **10**: 2222-30. (doi:10.1039/C7EE01764B)

[39] Schreier M, Héroguel F, Steier L, Ahmad S, Luterbacher J, Mayer M, Luo J, Grätzel M. 2017 Solar conversion of $CO_2$ to CO using Earthabundant electrocatalysts prepared by atomic layer modification of CuO. *Nature Energy*. **2**: 17087 (doi:10.1038/nenergy.2017.87)

# Costs of hydrogen production

## 6.1 Financial cost

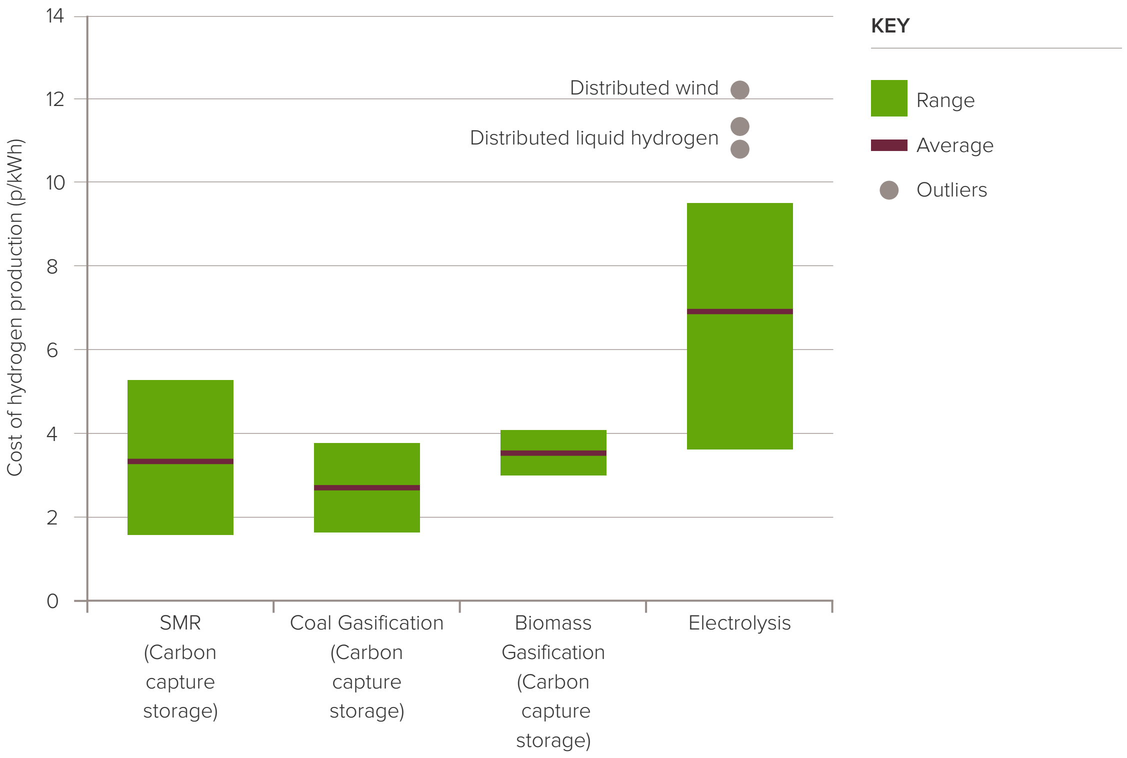
The costs of producing low-carbon hydrogen will be influenced by the cost of the feedstock, the capital cost of the plant, the scale of the process and the operating costs. The existing data is limited with wide ranges and uncertainties. Figure 10 presents the potential costs of established hydrogen technologies, adjusted to account for the additional cost of carbon capture and storage.

The costs of steam methane reforming hydrogen production are primarily influenced by the cost of natural gas and the costs and method of carbon capture and storage. Production costs (ie not including transportation through pipes, billing costs, taxes and levies) have been estimated to be in the order of 2 to 5 pence per kWh. The cost of production by electrolysis is dependent upon the cost and availability of electricity from renewable sources and is estimated to be between 4 and 9 pence per kWh. Whole system modelling will be necessary to comprehend the value of electrolysers for grid balancing and energy storage[40].

Producing hydrogen from the gasification of biomass with carbon capture and storage has not yet been proven at scale, but some models suggest a cost of between 3 to 4 pence per kWh hydrogen, excluding any benefit derived from negative emissions.

**FIGURE 10**

The cost of hydrogen produced from low-carbon hydrogen technologies[41]



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[40] Energy Research Partnership. 2016 Potential Role of Hydrogen in the UK Energy System. See http://erpuk.org/wpcontent/uploads/2016/10/ERP-Hydrogen-report-Oct-2016.pdf (accessed 16 November 2017).

[41] Sustainable Gas Institute, Imperial College London. 2017 A Greener Gas Grid: What are the Options? White Paper. See http://www.sustainablegasinstitute.org/a-greener-gas-grid/ (accessed 16 November 2017).

The majority of alternative production methods, for example involving microbes or solar to fuels methods are at the early stages of development. Therefore, future costs are uncertain and cannot be calculated until demonstrators are built.

A study commissioned by the Committee on Climate Change estimated prices for hydrogen production technologies into the future[42]. There are large assumptions included in these costs, but what is clear is that technologies using fossil fuels are unlikely to have significant future cost reductions and technologies such as biomass gasification and electrolysis have more potential to come down in price.

As mentioned in section 1.1, the location of hydrogen technologies and proximity to the end use will also have a large impact on cost. Hydrogen energy hubs are therefore likely to reduce costs considerably, particularly for electrolysers[43].

## 6.2 Carbon cost

How low-carbon are the various low-carbon hydrogen production methods? There are many variables that can be considered including the carbon capture and storage methods employed, feedstock delivery and plant construction. Estimates therefore cover a range of equivalent greenhouse gas emissions for each production method as shown in table 1. Few of the production technologies have the potential to reduce emissions down to or below zero.

**TABLE 1**

### Estimated greenhouse gas emissions for hydrogen production methods.

The greenhouse gas emissions from laboratory scale technologies for example solar to fuels have yet to be estimated.

| Production method | Greenhouse gas emission equivalent estimates ($gCO_2$/kWh of hydrogen)[44] |
|---|---|
| SMR with carbon capture storage | 23 to 150 |
| Coal gasification with carbon capture storage | 50 to 180 |
| Electrolysers with low-carbon electricity | 24 to 178 |
| Biomass gasification with carbon capture storage | -371* |
| Comparison natural gas for heating | 230 to 318 (methane) |

* One study provides an estimate of hydrogen production from biomass gasification using carbon capture and storage of -371 $gCO_2$eq/kWh[45]. Biomass gasification routes to hydrogen (without carbon capture and storage) emit up to 504 $gCO_2$/kWh.

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[42] E4 Tech, University College London Energy Institute, Kiwa Gastec. 2015 Scenarios for Deployment of Hydrogen in Contributing to Meeting Carbon Budgets and the 2050 Target. See https://www.theccc.org.uk/wp-content/uploads/2015/11/E4tech-for-CCC-Scenarios-for-deployment-ofhydrogen-in-contributing-to-meeting-carbon-budgets.pdf (accessed 16 November 2017).

[43] ITM-Power. 2017 Hydrogen Cost Structure Update. See http://www.itm-power.com/news-item/hydrogen-cost-structure-update (accessed 16 November 2017).

[44] Sustainable Gas Institute, Imperial College London. 2017 A Greener Gas Grid: What are the Options? White Paper. See http://www.sustainablegasinstitute.org/a-greener-gas-grid/ (accessed 16 November 2017).

[45] Susmozas A, Iribarren D, Zapp P, Linβen J, Dufour J. 2016 Life-cycle performance of hydrogen production via indirect biomass gasification with $CO_2$ capture. *International journal of hydrogen energy*. **9**:19484-91. (doi.10.1016/j.ijhydene.2016.02.053).

# Conclusion

The UK Government has estimated that hydrogen demand could be as high as around 700 TWh/year in 2050[46]. This briefing demonstrates that it is feasible to produce low-carbon hydrogen at scale.

The technologies examined are as follows:

- Steam methane reforming is a commercial technology and produces hydrogen on a large scale (nationally around 26.9 TWh/year), but is not currently low carbon. Innovative technology developments may help and research is underway. Further, carbon capture is essential. Alternative thermal methods of creating hydrogen indicate biomass gasification has potential, and is being piloted at 50 KW in the UK, with plans to build a commercial plant capable of 45 MW. Other techniques currently at a low technology readiness level include separation of hydrogen from hydrocarbons using microwaves.
- Commercial electrolysers are on the market and have been in use for many years. Further technology developments will enable new generation electrolysers to be commercially competitive when used at scale with fluctuating renewable energy sources.
- Biological routes to hydrogen through anaerobic digestion are feasible now at a laboratory and small pilot scale. However, this technology may prove to have additional or greater impact and value as route for the production of high value chemicals within a biorefinery concept.
- A number of experimental techniques have been reported, the most developed of which is solar to fuel, using water as the feedstock. The research is promising, though views are divided on its ultimate utility. Competition for space will always limit the scale up of solar to fuels.

Steam methane reforming and electrolysis are the most likely technologies to be deployed to produce low-carbon hydrogen in the near to mid-term, providing that the challenges of high levels of carbon capture (for steam methane reforming) and cost reduction and renewable energy sources (for electrolysis) can be overcome. The range of hydrogen production methods will need to be tailored to an appropriate size to match demand and location. Centralised and decentralised production infrastructure will bring different challenges. Increasingly, electrolysis would be suitable for grid balancing and off-grid deployment with renewables. The hydrogen demand from urban areas is more likely to require large-scale hydrogen production infrastructure such as steam methane reforming.

Whilst renewable energy sources must drive low-carbon hydrogen production, carbon capture use and storage will be essential in the transition phase.

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[46] HM Government. 2017 The Clean Growth Strategy See: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/651916/BEIS_The_Clean_Growth_online_12.10.17.pdf (accessed 23 November 2017).

The UK's strengths have been identified as:

- Steam methane reforming
  Catalysts are important in this process and the UK has world leading catalytic scientists and for example Johnson Matthey plc and John Wood plc as important commercial players in catalysts and plant. The UK also has expertise to address future challenges in, for example membranes and solid looping.
- Electrolysis
  In academic terms, the UK is strong in fundamental electrochemistry, modelling of electrochemical systems, materials design, testing and theory. It is also strong in electrochemical engineering of large-scale systems and is recognised internationally for electrochemical diagnostics and systems optimisation. The UK has a leading technology developer in ITM Power Ltd.
- Biological methods
  Biological production methods as well as biorefining technology and pre-treatment are research areas where the UK leads internationally.
- Solar to Fuels
  The UK has extensive strengths in advanced energy materials, solar photovoltaic materials and catalysis. Some of this is already targeting solar to fuels.

# Annex A: Definitions

**Low-carbon hydrogen**

Within this report, low-carbon (sometimes called clean or green) hydrogen is defined as hydrogen that is produced either from zero-carbon processes such as water electrolysis using renewable energy, or from a process where carbon capture use and storage is employed. Additionally, a whole life-cycle analysis of the hydrogen production method should indicate minimal emissions in line with the global reduction in emissions implied by the Paris Accord.

There is currently no clear internationally accepted definition of green hydrogen. Efforts are being made in projects such as the EU CertifHy accreditation program to certify the origin of hydrogen supplies and to define green hydrogen. This will become increasingly important as monitoring of greenhouse gas emissions becomes more stringent in line with global efforts to reduce emissions.

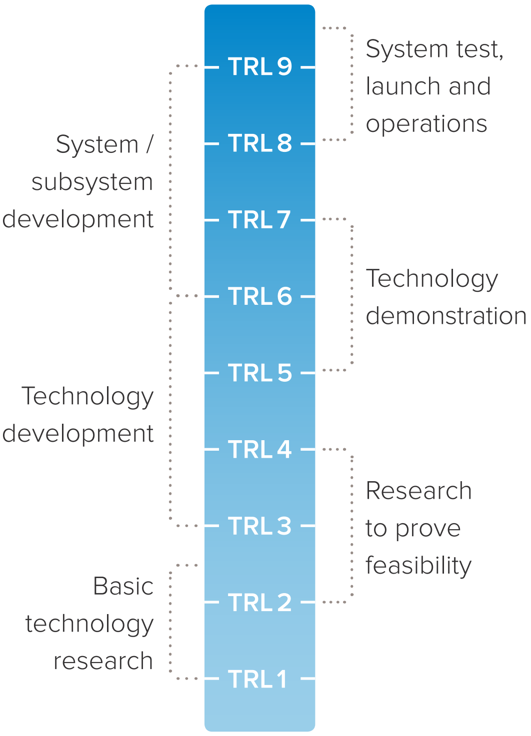
**Technology readiness levels (TRL)**

Technology Readiness Levels (TRLs) are a technology management tool that provides a measurement to assess the maturity of evolving technology.

**FIGURE 12**

Technology readiness levels (TRL).

| System | Technology readiness level (TRL)[47] |
|---|---|
| Steam methane reforming with carbon capture and storage | 8 |
| Autothermal reforming | High TRL |
| Coal gasification with carbon capture and storage | 7 |
| Alkaline electrolysers | Mature |
| Polymer electrolyte membrane electrolysis | 5 – 7 |
| Biomass gasification with carbon capture and storage | 4 |
| Solid oxide electrolysers | 3 – 5 |
| Biological methods | 1 – 3 |
| Solar to Fuels | 1 – 3 |



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[47] https://www.theccc.org.uk/wp-content/uploads/2015/11/E4tech-for-CCC-Scenarios-for-deployment-of-hydrogen-in-contributing-to-meetingcarbon-budgets.pdf

**Energy hub**
An area where energy can be flexibly converted, conditioned, and stored using a variety of energy infrastructures ideally suited to the local energy system.

**Grid balancing**
To avoid power cuts, the generation (supply) of electricity must match the demand for electricity from consumers at all times. This is known as grid balancing.

**Units used in the report.**
In the International System of units (SI), energy is measured in joules (J). Power is the rate of energy used and is measured in joules per second or watts (W).

The SI system uses the following scale prefixes:

To simplify the numbers (eg for domestic energy bills), energy is sometimes quoted in watt hours (Wh), which is the amount of energy used at a rate of one watt for one hour = 3,600 Joules.

For example: running a 1,000 watt (1 kW) heater for 1 hour has used 1,000 Wh or 1 kWh of energy (if expressed in joules this would be 3,600,000 J or 3.6 MJ)

For hydrogen storage and use, the energy content is often expressed in multiples of watt hours eg MWh, GWh, TWh.

The rate of production of hydrogen is given in multiples of watts eg MW, GW.

TABLE 2

| Number | Name | Symbol |
|---|---|---|
| 1,000 | Kilo | k |
| 1,000,000 | Mega | M |
| 1,000,000,000 | Giga | G |
| 1,000,000,000,000 | Tera | T |
| 1,000,000,000,000,000 | Peta | P |

# Annex B: Acknowledgements

This policy briefing is based on discussions from a workshop held at the Royal Society on 19th July 2017 and subsequent input. The Royal Society would like to acknowledge the contributions from those people who attended the workshop, and helped draft and review the policy briefing.

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