H2FC SUPERGEN
THE HYDROGEN AND FUEL CELL RESEARCH HUB

THE ROLE OF HYDROGEN AND FUEL CELLS IN DELIVERING ENERGY SECURITY FOR THE UK

A H2FC SUPERGEN White Paper

Extended summary

March 2017

UNIVERSITY OF BIRMINGHAM
UCL
Imperial College London

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BACKGROUND

This White Paper has been commissioned by the UK Hydrogen and Fuel Cell (H2FC) SUPERGEN Hub to examine the roles and potential benefits of hydrogen and fuel cell technologies in delivering energy security for the UK.

The H2FC SUPERGEN Hub is an inclusive network encompassing the entire UK hydrogen and fuel cells research community, with around 100 UK-based academics supported by key stakeholders from industry and government. It is funded by the UK EPSRC research council as part of the RCUK Energy Programme. This paper is the second of four that were published over the lifetime of the Hub, with the others examining: (i) low-carbon heat; (iii) future energy systems; and (iv) economic impact.

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HEADLINE MESSAGES

Hydrogen is a fuel that offers zero point-of-use emissions and can be produced from a wide variety of energy input. **Fuel Cells** are a conversion technology that allows high efficiencies of energy supply. The UK energy security strategies do not yet embrace the potential these technologies offer. This White Paper therefore describes how hydrogen and fuel cells can contribute to energy security.

Our key messages are:

Fuel cells can contribute to UK energy system security, both now and in the future. Fuel cells can uniquely generate electricity at high efficiencies even at very small scales, and are already being increasingly used for emergency back-up power. There are many types; some require high-purity hydrogen, while others can operate on a range of fuels including natural gas, allowing them some degree of flexibility. In the longer term, fuel cell electric vehicles could greatly reduce oil dependence in the transport sector and fuel cell micro-CHP could reduce gas consumption by generating electricity and heat at high overall efficiencies.

Hydrogen can be produced using a broad range of feedstocks and production processes, including renewable electricity. Price volatility of primary energy sources or supply disruptions can be ameliorated by switching to other energy sources. Building a diverse portfolio of hydrogen production plants, using a range of feedstocks, would cost little more than building only the cheapest plant.

Adopting hydrogen as an end-use fuel in the long term increases UK energy diversity. Scenario analyses using an energy system model show that the diversity of the UK energy system, including primary energy consumption, electricity generation, heat and transport, would be similar for scenarios with and without hydrogen, and slightly improved compared to today’s situation.

Hydrogen can be safely transported and stockpiled. Hydrogen pipelines are widely-used in industry and well-understood. It would be possible to develop large-scale storage of hydrogen more cheaply than that for electricity. This could supply many of the same markets as electricity and increase diversification compared to a system focused on electrification of heat and transport.

Hydrogen and fuel cells could improve the stability of a low-carbon electricity system with a high penetration of renewables. Hydrogen could be produced from renewable electricity using electrolysers in a process called power-to-gas. The hydrogen could then be used as a fuel (e.g. in the transport sector), or stored and used to generate electricity at times of high demand. UK energy resource independence could be greatly increased through deploying high levels of renewables supported by hydrogen and fuel cells.

A decentralised system of hydrogen and fuel cells could improve the resilience of the energy system to threats such as terrorism, production plant and infrastructure failures, and natural disasters. Furthermore, decentralised generation that operates at peak times (such as micro-CHP on winter evenings) would reduce demand peaks needed by centralised generation systems, improving reliability and reducing the need to invest in peak generation plant.

With respect to affordability, the Government's energy security strategy concentrates on short-term resource price volatility and insufficiently addresses long-term sustainability. The strategy does not provide a comprehensive, long-term outlook for the development of a resilient, low-carbon electricity system at long-term stable costs that also includes costs to the taxpayer not covered by customer pricing. Production and infrastructure investments have long lifetimes and need a reliable and stable framework that will deliver affordable cost to the society as a whole.

The energy security strategy needs to consider the implications of closer interactions between the power, gas and transport sectors in the future. These markets will be intimately linked by using hydrogen and fuel cells across the various transport, power, and heating applications. A future strategy would ideally take a more holistic view of these markets and of the energy system.

Hydrogen and fuel cells offer many options to improve the diversity, reliability, resilience and sustainability of the UK energy system in the future. With appropriate support and a clear and reliable policy framework, UK energy security can be improved in the long term by unfolding the great potential that lies in the use of these technologies.

EXTENDED SUMMARY

The impacts of low-carbon technologies on energy security have received little attention in the literature, with the exception of renewables integration into the electricity system. This White Paper assesses the potential implications of deploying hydrogen and fuel cells on UK energy security. It first examines the technologies individually, then assesses potential impacts of these on the electricity, gas, and transport systems, and finally considers their energy security implications for the whole UK energy system.

The energy security challenge in a low carbon energy system

Energy security is one of the core dimensions of energy policy of governments worldwide, together with affordability and environmental sustainability. The UK government identifies energy security as a framework in which consumers have access to the energy services needed (physical security) at prices that are not excessively volatile (price security). Energy security is seen in terms of both securing supplies and securing the delivery of end products to UK consumers for heat, power, and transport.

In the last few decades, the UK has experienced a high level of energy security, with indigenous fossil fuel resources, a very stable electricity system and robust delivery systems. Energy crises have primarily had domestic causes (e.g. coal miner strikes in the 1980s and petrol tanker strikes in 2000). One challenge for the UK is related to the depletion of UK oil and gas reserves, and subsequent geopolitical risks of fossil fuel access. Hydrogen produced from renewable sources would offer greater energy resource independence for the UK and for other countries, with close-to-zero CO_2 emissions.

The UK dropped to 11th position in the World Energy Council's (WECs) Energy Trilemma Index in 2016. This index assesses a country's energy security, energy equity, and environmental sustainability simultaneously.[1] By another measure the UK's global energy security ranking has been lowered in the last few years, dropping to 6th place for the first time in 2014 in the International Index for Energy Security Risk assessment by the US Chamber of Commerce.[2] This change can be attributed to the rising uncertainty in the UK's energy policy, with significant challenges that need to be addressed, including:

- the closing of around a fifth of current power stations by 2020, as they come to the end of their working life or are deemed too polluting under regulations such as the EU Industrial Emissions Directive (IED);
- the need to decarbonise electricity generation to ensure that the UK can meet its legally-binding CO_2 emission reduction targets to cut greenhouse gas emissions by 80% in 2050, compared to 1990; and,
- the decline of reserves of fossil fuels in the UK Continental Shelf (UKCS), which makes the UK increasingly dependent on imports at a time of rising global demand, uncertainty in markets, and increased resource competition.

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[1] Wyman O. World Energy Trilemma Index. London, UK: World Energy Council; 2016.

[2] Institute for 21st Century Energy. International Index of Energy Security Risk. U.S. Chamber of Commerce. Washington, D.C., USA; 2016.

The challenge for the Government is to maintain a secure energy system as the UK's fossil energy resources dwindle and as the energy system is transformed to reduce greenhouse gas emissions.

Definitions of energy security

There is no single accepted definition of energy security. A number of approaches have been proposed from economics, engineering, political science, system studies and natural science to assess energy security, but these tend to be one-off rather than holistic studies. Very little consideration has been given to analysing energy security in the context of future low-carbon energy systems.

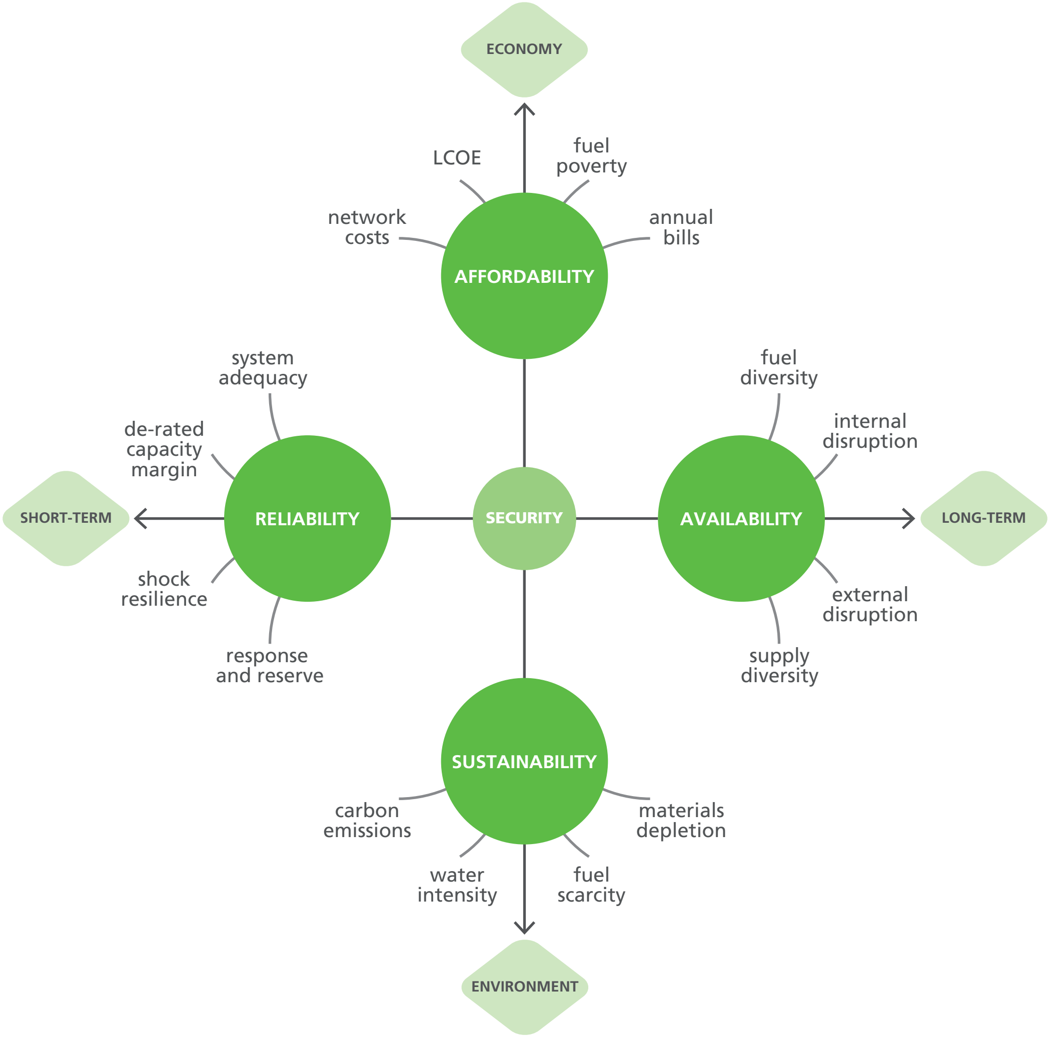
One approach defines energy security in terms of the 'Four A's':

- Availability: ensures that energy supplies are available in sufficient amounts.
- Affordability: aims to have these resources available at competitive prices.
- Accessibility: focuses on ensuring all citizens have access to energy.
- Acceptability: minimising the negative impacts of energy, such as pollution and environmental damage.

For this White Paper, a modified version of this approach was preferred that better accounts for long-term viability. The approach presented in Figure S1 was adopted and applied to resources, energy supply and infrastructure in the UK energy system:

- Availability: access to primary energy resources.
- Affordability: the cost incurred by energy supply and infrastructure at a societal level.
- Reliability: resilience of the energy infrastructure.
- Sustainability: long-term environmental impact.

Figure S1 Framework for the assessment of low carbon energy security (LCOE is levelised cost of energy).[3]



Hydrogen production from a range of feedstocks

Hydrogen is the only zero-carbon energy carrier (i.e. with no emissions at point-of-use) other than electricity that is under serious consideration in the UK. It can be used to power high-efficiency fuel cells, to provide energy storage at a range of scales, as a supplement or replacement for natural gas, and as a vehicle fuel. Whilst the advantages of using hydrogen for increasing and sustaining energy security are discussed in this White Paper, a broader discussion on its role in the energy system can be found in the H2FC Hub White Paper on Energy Systems.[4]

Hydrogen does not occur naturally and needs to be converted from chemical compounds – most commonly from water or from hydrocarbons such as methane (natural gas), requiring an energy input. Hydrogen is therefore described as an

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[3] Concept taken from: Cox E. Assessing the future security of the UK electricity system in a low-carbon context. BIEE 14th Academic Conference; 2014.

[4] Staffell I, Dodds PE. The role of hydrogen and fuel cells in future energy systems. London, UK: H2FC SUPERGEN Hub; 2017.

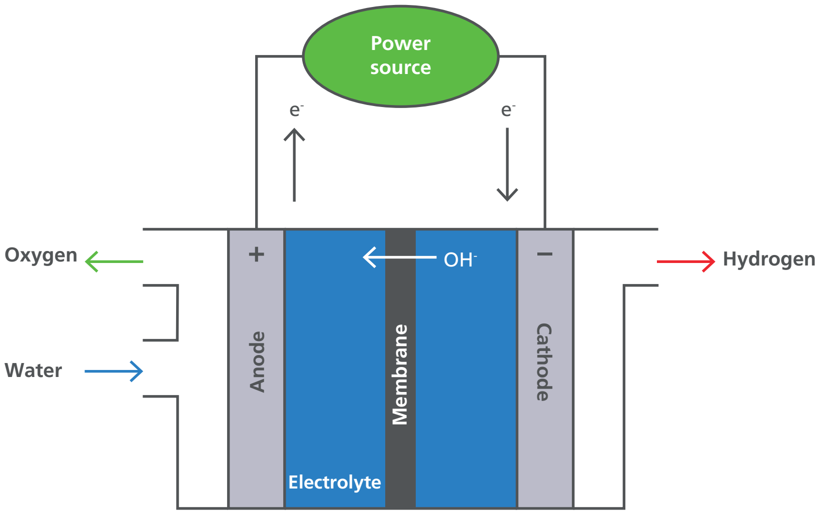
energy vector or fuel that serves as input to energy conversion processes delivering electricity or heat.

Hydrogen can be produced using a range of processes, from a variety of feedstocks. Around 50 million tons of hydrogen are produced each year from natural gas, coal, oil, and to a lesser extent electricity, for industrial uses around the world. The choice of production technology currently depends primarily on the feedstock availability and overall cost.

Coal gasification plants have been in operation for the last two centuries, producing a syngas (town gas) mainly containing hydrogen and carbon monoxide, whilst methane reforming has been used to produce hydrogen from natural gas over the last century. These technologies are mature and the principal challenges going forward are to supply low-carbon hydrogen at an acceptably low cost. All of these technologies produce high CO_2 emissions, which depend on the carbon content of the feedstock. For steam–methane reforming (SMR) of natural gas, emissions are approximately 250 $gCO_2/kWh\ H_2$. These emissions could be avoided, although not completely, using carbon capture and storage (CCS).

The other principal way of producing hydrogen is by electrolysis, which uses electricity to split water molecules (Figure S2). This produces high-purity hydrogen with a zero to low-carbon footprint if renewable electricity is used. However, if the input electricity is generated in fossil fuel plants and has a high carbon intensity, then electrolysis may lead to a higher carbon footprint than unabated SMR. The key challenges for electrolysis are to reduce capital costs, supply low-carbon electricity, and improve the conversion efficiency.

Figure S2 **Schematic illustration of a water electrolyser with an alkaline electrolyte.**



A number of novel hydrogen production methods are under development, such as bio-hydrogen from algae and photocatalytic hydrogen production from sunlight and water. They are still at the laboratory stage but could become important over the coming decades, if their development is sufficiently supported.

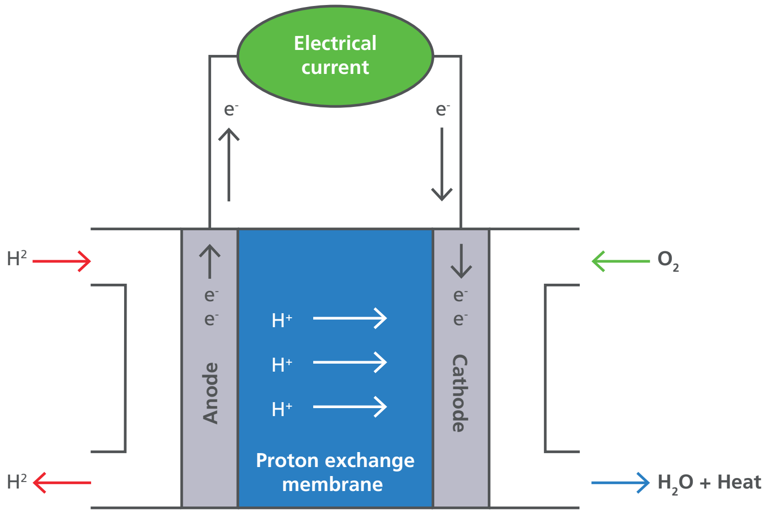
Hydrogen can be used to synthesise methane in order to produce synthetic natural gas (SNG), which can substitute for natural gas or be used to synthesise methanol. Hydrogen can also be used as a storage medium for electricity since it can be produced using electrolysis (power-to-gas), stored and then used to generate electricity in fuel cells or gas turbines.

Fuel cells

Fuel cells electrochemically combine a fuel, typically hydrogen, and oxygen (from air) to produce electricity, water and heat. They differ from batteries in that the reactants are continuously supplied, rather than being stored internally, and hence can operate continuously. Fuel cells do not have the same energy efficiency limits as thermal conversion processes and generally have high electrical efficiencies no matter how large or small the unit size, in contrast to thermal-based electricity generation that can only achieve similar efficiencies at large scales. The modular design of fuel cells alongside their ability to efficiently generate electricity without producing pollutants makes them suitable for a wide range of applications and markets.

Fuel cell types are distinguished by the input fuel, electrolyte material and operating temperature. Low-temperature fuel cells include polymer electrolyte fuel cells (PEFCs), using high-purity hydrogen as a fuel, and alkaline fuel cells (AFCs), with slightly lower-purity demands. Figure S3 shows the operating principle for a PEFC running on hydrogen. Intermediate and high-temperature PEFCs (IT- and HT-PEFC) and phosphoric acid fuel cells (PAFCs) operate in the 120°C to 200°C temperature range with fewer limitations on the quality of the hydrogen fuels. High-temperature fuel cells such as molten carbonate fuel cells (MCFCs), and solid oxide fuel cells (SOFCs) operate at higher temperatures between 600°C and 900°C and can use both hydrogen and hydrocarbons, including natural gas, as a fuel.

Figure S3 Schematic illustration of a polymer electrolyte fuel cell (PEFC) operated on hydrogen.



The high-purity hydrogen required by low-temperature fuel cells would typically be produced by electrolysis or with adequate purification from other hydrogen production processes. High-temperature fuel cells can produce electricity at higher efficiencies (55% to 65% net delivery to the grid) with less complex systems. Fuels for high-temperature fuel cells include hydrogen, syngas (hydrogen and carbon monoxide mix), methane, natural gas, biogas, propane, butane, methanol and ethanol. This means that they could underpin a transition from natural gas to a future low-carbon gas supply, for example based on hydrogen and synthetic natural gas.

Fuel cell emissions consist of only water, if run on hydrogen, and water and carbon dioxide, if run on fuels containing carbon. Virtually no air quality pollutants (e.g. SO_2, NO_x, CO, particulate matter, etc.) are produced. They operate with very little noise and have little need for maintenance as they have few moving parts.

The applications of fuel cells span from a few watts to 100 MW_{el}, including portable electricity generators, small consumer devices, vehicles and stationary power generation. They can act as uninterruptible power supplies (UPS) in protecting data centres and other key infrastructure from grid failures, and supply power in locations far removed from grid access. Due to their modularity, fuel cells typically are employed in decentralised applications, offering electricity grid support, CHP installations and black start capability.

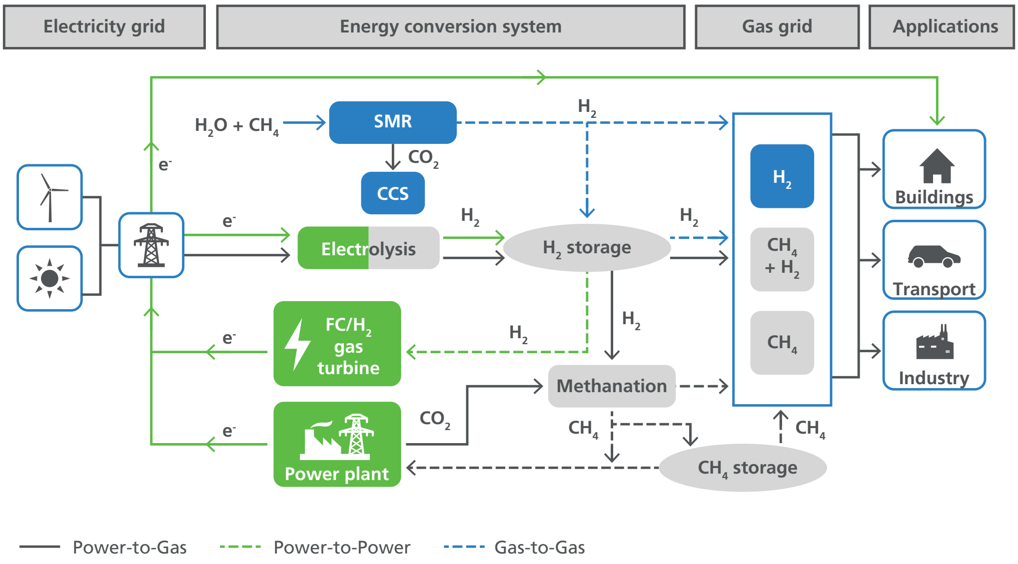
Access to Energy Sources

Hydrogen can be produced from a broad range of feedstocks. Short- to long-term commodity price hikes or supply interruptions could be mitigated by switching to other energy sources for hydrogen production, although this would require additional investments in production plants with low capacity factors. Hydrogen offers similar advantages to electricity in this regard. Since hydrogen can be produced by electrolysis from renewable generation and by biomass gasification, it offers the opportunity to reduce import dependence on fossil fuels.

Hydrogen could support a low-carbon electricity system in the future through the conversion of surplus renewable electricity by electrolysis. The resulting hydrogen could, for example, be sold into the transport fuels market, stored for times of peak electricity demand, or sold as a chemical process feedstock. Power-to-gas technology (Figure S4) is one of the key pathways that link the electricity and gas markets. Whilst storage of electricity at large scale remains a challenge, bulk gas storage of hydrogen in salt caverns has been carried out for many years, including on Teesside in the UK.

Gas transmission via pipeline and distribution networks offers a number of further advantages for bulk distribution such as linepack storage capacity of the gas transmission and distribution networks. Hydrogen can be used to produce synthetic natural gas (SNG) with waste CO_2 and injected into the existing gas infrastructure.

Figure S4 **Schematic diagram showing the three main energy conversion pathways (power-to-gas, power-to-power and gas-to-gas) in a renewable energy integrated energy system.**[5]



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[5] Brandon N., Kurban Z. Clean Energy and the Hydrogen Economy. Philosophical Transactions of the Royal Society. 2017.

Resilience of Energy Systems

Fuel cells are an inherently decentralised technology since units are rarely larger than a few MW_{el}. They can support electricity grid functions at a local level to:

- reduce electricity distribution losses;
- increase system reliability due to lower probability of total power disruption;
- allow black start capability and the option to 'island' those parts of a grid that are still intact following an outage;
- supply balancing power to stabilise electricity grids with high renewable electricity penetration; and,
- increase fuel economy, thus reducing operating costs and any impact of fuel price volatility.

Such a distributed system would be more robust, since the probability that the complete system could fail would be very low. Moreover, parts of the grid could be restarted without having to wait for major repairs, for instance following the loss of a large power station or major distribution line. The threat of any disasters or malevolent acts occurring in the energy infrastructure (ranging from weather events to sabotage and cyber-attacks) would be greatly reduced.

Combining the variety of fuels on which the different fuel cell types operate with the wide range of hydrogen production feedstocks would add an element of flexibility to the energy system that has hitherto not been available. Dependence on single primary energy sources such as coal, natural gas and oil would be greatly reduced. The gas infrastructure would take over part of the services of the electricity grid in balancing power distribution (power-to-gas-to-power). If fuel cell electric vehicles were widely adopted, then these could also generate electricity to supply buildings (for instance during emergencies or blackouts), as already demonstrated by the Toyota Mirai vehicles in Japan.

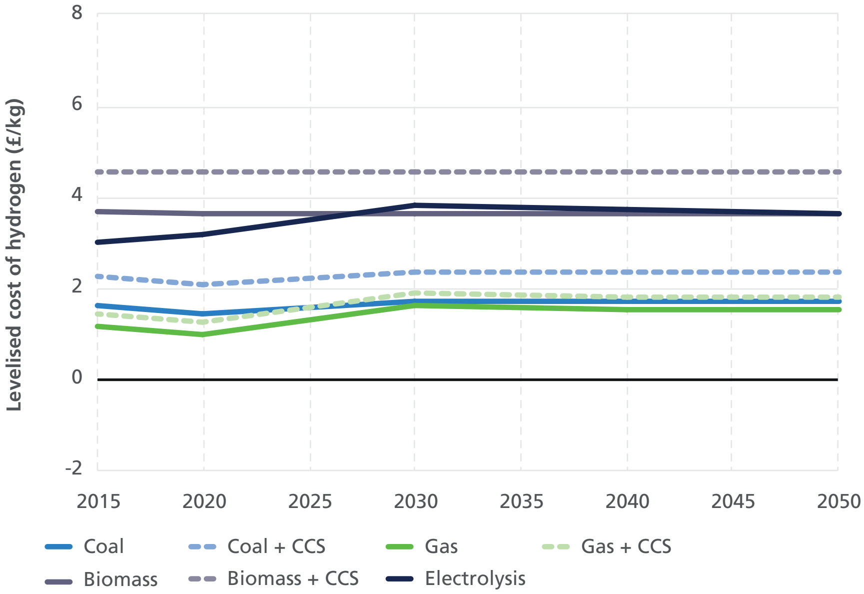
Affordability of Energy Services

Hydrogen is more expensive to produce than existing fossil fuels, but this would change in the future if a high-enough price on carbon were applied (Figure S5) and if the costs of externalities such as air pollution were internalised. Modelling using the UK TIMES energy system model shows that hydrogen could be produced economically from a range of feedstocks in the future. Markets could switch fuels and production processes in response to feedstock price volatility, if redundant hydrogen production plants were available, in a similar way to electricity at present. The capital investment required to build semi-redundant plants would increase the cost of the produced hydrogen, so there would be a trade-off between flexibility and cost.

One method to measure energy security is through fuel diversity, as more diverse systems are likely to be more resilient to an interruption to part of the system. The scenarios suggest that the energy system diversity as measured by the Shannon-Weiner Index is likely to change in the future, with increases in some areas and decreases in others. Hydrogen tends to increase diversity over strategies that focus on electrification, but not in all parts of the system or in all circumstances.

In all of the scenarios, natural gas SMR with CCS is primarily used to produce hydrogen, with energy commodity import dependence increasing over time. Yet an alternative strategy with a portfolio of diverse hydrogen production and electricity generation technologies could be followed at low additional cost, and is a potential long-term option for the UK government. Reducing reliance on energy commodity imports, on the other hand, would be much more expensive, and alternative strategies would likely be more cost-effective.

Figure S5 Levelised cost of hydrogen production forecasts for the UK from a range of sources, with a CO_2 price increasing from £50/tCO_2 in 2020 to £250/tCO_2 in 2050. No environmental levies are placed on electricity in this diagram.



Details of data sources and calculation procedure can be found in the full text in Chapter 5.

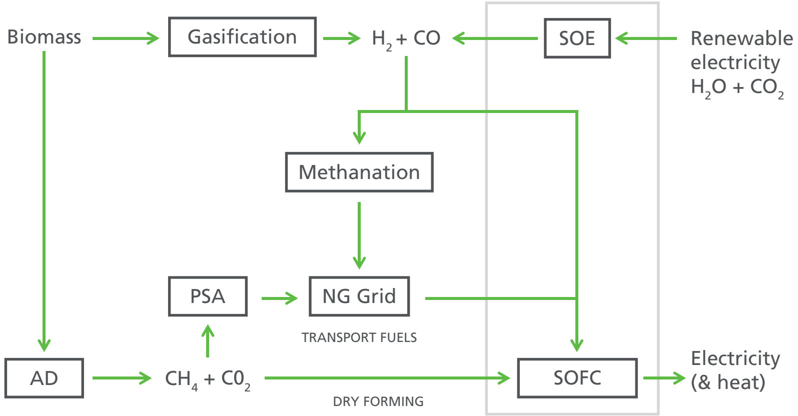
Sustainability of the energy system

Although hydrogen can be produced from coal, oil, and natural gas, CCS facilities would be required to produce low-carbon hydrogen to meet UK emission targets. There are engineering, economic and environment challenges to using CCS that still need to be resolved.

Hydrogen and synthetic methane, produced from low-carbon sources and used in high efficiency fuel cells, offer an approach to a fully decarbonised energy system. The higher efficiency of fuel cells on a far broader scale of rated power, compared to heat engines and most thermal power stations, reduces energy consumption whilst at the same time improving air quality at the point of use. Only the largest new-builds in power generation can compete with fuel cell efficiency levels. When installing a micro-CHP based on fuel cells in a residential building, though, the fuel cell would compete with the conventional electricity generation average value, which is below 40%, including transport losses.

Using the electrochemical fuel cycle displayed in Figure S6 would allow the use of renewable energy inputs in the form of primary electricity (solar, wind, ocean etc.) and biomass/waste to drive a fully decarbonised conversion cycle of primary energy and zero-carbon fuels based on the existing natural gas infrastructure, and in future morphing into a decarbonised infrastructure using biogas, hydrogen and SNG. The issue of overall efficiency has to be addressed appropriately, though, especially if any non-renewable energy is involved. The economic viability of such as system would also need to be demonstrated. The result would be a fully sustainable system with a high degree of national independence from fuel imports, and with low price volatility.

Figure S6 Production of synthetic natural gas (SNG) via biomass conversion in gasification or anaerobic digestion, and from power-to-gas with subsequent methanation. SOFC is a solid oxide fuel cell. SOE is solid oxide electrolysis. AD is anaerobic digestion. NG is natural gas. PSA is gas purification by pressure swing adsorption.



Policy implications

UK's Energy Security Strategy

The Government's approach to energy security was outlined in the Energy Security Strategy (ESS) document, published by DECC in 2012. BEIS and Ofgem review this strategy annually and publish updates in the Statutory Security of Supply Report (SSSR), which provides the Government's plans for energy security with a four-year outlook.

The UK Government's primary energy security concern is 'ensuring that consumers have access to the energy services they need (physical security) at prices that avoid excessive volatility (price security)'. The focus on consumers means that the approach to energy security is concerned with the whole energy system, from primary resources to distribution networks. The definition of price security focuses on excessive volatility. It currentlyn does not take any account of long-term affordability, either in terms of resource price trends or the impact of transitioning to a low-carbon economy.

The ESS has a strong focus on the electricity system, with recognition that closing down older coal and nuclear power stations and deploying renewables will create capacity and balancing challenges, requiring investment in infrastructure and the development of new infrastructure technologies such as storage and interconnection. However, beyond these recommendations on specific areas of investment, it does not provide a comprehensive, long-term strategy on how to ensure these challenges will be met or when they will be met. Since de-rated supply margins reduced to around 1% without balancing services, the Electricity Market Reform (EMR) policy framework has been created that establishes new markets, some of which might provide opportunities for fuel cells in the future. Hydrogen could also contribute by supplying low-carbon peak power generation in turbines or gas engines.

Maintaining security of the gas supply, which currently has significantly higher supply margins than the electricity system (24% in 2016 supply capacity) appears less of a challenge today. The reduction in domestic production will lead to increasing reliance on imports, including from Norway and the Netherlands, but also from further afield in the form of liquefied natural gas (LNG) imports. The Government aims to strengthen the UK's bilateral trading links and promote liberalisation of EU gas markets to help secure imports in the future. Yet there is much uncertainty in the international gas price, with evolving demands and supply (e.g. shale gas exports from the USA), while Brexit might affect the availability of gas from the EU during any regional disruption.

The UK has an imbalance of petroleum products, with a surplus of petrol but a deficit of diesel and aviation fuel, which is imported from Europe and the Middle East. In the longer term, the UK will become increasingly reliant on oil imports and the case for increasing strategic oil reserves might need to be revisited. Hydrogen as a transport fuel will help to increase such reserves.

Realising the benefits of hydrogen and fuel cell for energy security

A more holistic and long-term approach to energy security could underpin the development of a more flexible, low-carbon energy system. Scenario modelling shows that resource diversity would likely increase if hydrogen were adopted, compared to a no-hydrogen scenario, but could be increased much more through forward planning and small further investments. Production and infrastructure investments have long lifetimes and an energy security policy that considers only the short to medium-term is not likely to lead to investments that maximise energy security in the long term.

Supporting the electricity system with hydrogen and fuel cells, through power-to-gas and peak generation, and using hydrogen for both heating and transport, will lead to closer interactions between the power, gas and transport sectors in the future. A strategy would ideally consider these interactions and take a more holistic view of these markets and of the energy system as a whole. It would identify acceptable levels of energy security across the system and how they could be achieved.

Indications by the Government of future policies in hydrogen and fuel cells are needed to support the long-term perspective of the transition to a low-carbon economy. Incentives and regulation are needed to for instance support and define a market framework for electrolysers to provide system services improving the reliability and operation of the electricity network. This includes understanding load fluctuation levelling and avoiding or deferring grid reinforcement as business cases in the larger societal interest. Hydrogen produced from renewable sources has a carbon benefit, but cannot compete with fossil and nuclear fuel in the absence of taxes or levies that acknowledge its benefits in avoiding environmental and health impacts.

Final summary

Adopting hydrogen and fuel cell technologies could make an important contribution to improving energy security in a number of ways:

- Diversity and affordability: hydrogen can be produced economically from a diverse range of feedstocks, potentially reducing price volatility.
- Diversity of resources: hydrogen increases resource diversity over strategies that focus on electrification.
- Reliability: hydrogen can help to integrate high levels of renewables into the electricity system.
- Resilience: fuel cells run on a diverse set of fuels and could enhance resilience and reliability of networks by supporting distributed power generation, with reduced vulnerability to disturbances.
- Resilience: hydrogen offers low-cost, zero-carbon energy storage.
- Sustainability: fuel cells and hydrogen can improve air quality through very low pollutant emissions and no CO_2 emissions at point of use.

A revised energy security framework with a more long-term view could underpin improvements in UK energy security through targeted future infrastructure investments in low-carbon technologies. A clear and reliable policy framework will enable the Government, industry, and academia to work together to determine how best to ensure the country's energy security during the transition to a low-carbon energy system.

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