OPPORTUNITIES FOR HYDROGEN AND FUEL CELL TECHNOLOGIES TO CONTRIBUTE TO CLEAN GROWTH IN THE UK

A H2FC SUPERGEN White Paper

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THE HYDROGEN AND FUEL CELL RESEARCH HUB

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A H2FC SUPERGEN WHITE PAPER

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BACKGROUND

This paper has been commissioned by the UK Hydrogen and Fuel Cells Supergen Hub to examine the opportunities for hydrogen and fuel cell technologies to contribute to clean growth. It assesses the strength of the UK hydrogen and fuel cells sector using a range of metrics and recommends actions to underpin the development of a substantial export-focused industry.

The Hydrogen and Fuel Cells Supergen Hub is an inclusive network encompassing the entire UK hydrogen and fuel cells research community, including academia, industry and government. It is funded by the UK EPSRC research council as part of the RCUK Energy Programme (grant EP/P024807/1). The paper was funded through the Hub's flexible fund.

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All views expressed in this paper are those of the authors alone and do necessarily represent the views of their employers or the Hydrogen and Fuel Cells Supergen Hub.

ABBREVIATIONS

Abbreviations

APC	Advanced Propulsion Centre
BEIS	Department for Business, Energy & Industrial Strategy
CCC	Committee on Climate Change
CCS	Carbon capture and storage
CGE	Computable general equilibrium (economic model)
CHP	Combined heat and power
DRI	Direct reduction of iron
EPSRC	Engineering and Physical Sciences Research Council
ERDF	European Regional Development Fund
EU	European Union
H2FC	Hydrogen and fuel cell
HGV	Heavy goods vehicle
IEA	International Energy Agency
ISCF	Industrial Strategy Challenge Fund
MEA	Membrane electrode assembly
Mt	Million tonnes
OECD	Organisation for Economic Co-operation and Development
OLEV	Office for Low Emission Vehicles
PEM	Proton-electrolyte membrane (fuel cell)
R&D	Research and development
RD&D	Research, development and demonstration
RTA	Revealed technology advantage
SHFCA	Scottish Hydrogen and Fuel Cell Association

UAV	Unmanned aerial vehicle
UKHFCA	UK Hydrogen and Fuel Cell Association
UKRI	UK Research and Innovation
ULEV	Ultra-low emission vehicle
v/v	Fraction of a gas in a gas stream in volume terms (rather than mass or energy terms)

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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

There is a growing focus in many countries on the roles that hydrogen and fuel cell (H2FC) technologies are likely to have in their future low-carbon energy systems. This report examines whether the UK is well placed to develop and secure some of the economic opportunities associated with this market, both in the UK and abroad, as part of the UK Government's focus on clean growth.

Potential future markets for hydrogen and fuel cells

We examine the potential future markets for hydrogen and for fuel cells by comparing a range of UK and global energy decarbonisation studies. A clear pattern emerges from UK scenarios:

Importance of hydrogen and fuel cells

Hydrogen is important because it is one of three key zero-carbon vectors for decarbonising economies in the future, along with electricity and hot water. The UK Government's Clean Growth Strategy and the UK Committee on Climate Change have identified hydrogen as the most cost-effective option for decarbonising several parts of the UK energy system.

Fuel cells convert fuels, including hydrogen, to electricity and heat. Fuel cells are important because they can generate electricity at higher efficiencies than most internal combustion engines, and with no emissions. For road transport, this means that they have a higher fuel economy than cars powered by engines.

- Fuel cells are well suited to heavy-duty trucks and buses, and could power cars and trains.
- The gas networks could be converted to deliver hydrogen instead of natural gas to homes and businesses.
- Iron and steel, chemical feedstocks, and high-temperature processes could mostly be altered to use hydrogen.
- Hydrogen could integrate renewables and provide energy storage and flexible peak generation.

UK hydrogen consumption increases from 0.7 million tonnes (Mt) each year at present to 3–19 Mt by 2050 in these scenarios. The value of the hydrogen fuel alone would be £4bn–£28bn each year, and the value of vehicles, boilers, and other end-use devices would also be substantial.

Global hydrogen demand of more than 500 Mt is projected, with a value of at least £380bn. This market could offer substantial export opportunities for bulk hydrogen and for H2FC technologies in the transport, industry, building heat, and electricity generation sectors.

The UK's strengths in emerging hydrogen and fuel cell value chains

We have identified 196 companies working on H2FC technologies, ranging from micro spin-offs to multinational companies with H2FC divisions. Consulting, transport, and fuel cells are the most common market areas, but companies work across the whole supply chain. Companies are located across the UK, roughly in proportion to economic activity and population (Figure ES1). These companies have world leading fuel cell, hydrogen production, and material technologies, and some have secured substantial foreign direct investment. We analysed patent rates to estimate the relative technological capabilities of UK companies. The UK has been consistently within the top ten countries globally, but is still an order of magnitude behind Japan and the USA. Nevertheless, the UK has a greater share of H2FC patents than non-H2FC low-carbon energy patents.

Findings from a survey of UK companies

We surveyed the 196 companies and received 32 responses. Responding companies have an international outlook, with 60% of respondents having joint R&D with a European partner and 33% with a partner in North America. Two thirds are exporters.

Respondents think the UK has a good business environment for innovation and business development. Companies rely primarily on a range of R&D funding sources:

- R&D tax credits
- Innovate UK grants.
- European Union (EU) grants, for funding and as an enabler of joint R&D programmes with European partners.

Respondents highlight two funding issues. First, funding processes and decisions are slow and excessively bureaucratic, and this has prevented some smaller companies from accessing funding grants. Second, access to EU programmes is in doubt following Brexit.

A weak future UK market for H2FC technologies is a key issue for respondents. Many H2FC technologies are on the cusp of commercialisation, but costs are still higher than for incumbent technologies, and will only decrease with innovation and scale. Virtually all UK companies operate in the UK market, but near-term markets are seen as most likely to grow outside the UK. UK policy support for the development of domestic H2FC markets is considered poorer than in the European Union, North America and East Asia. Other countries have provided grants to bridge the cost difference or have used public procurement to grow a market, with the aim of building domestic industries as future export industries. The lack of a domestic market might be one underlying reason why many surveyed companies struggle to access finance for growth.

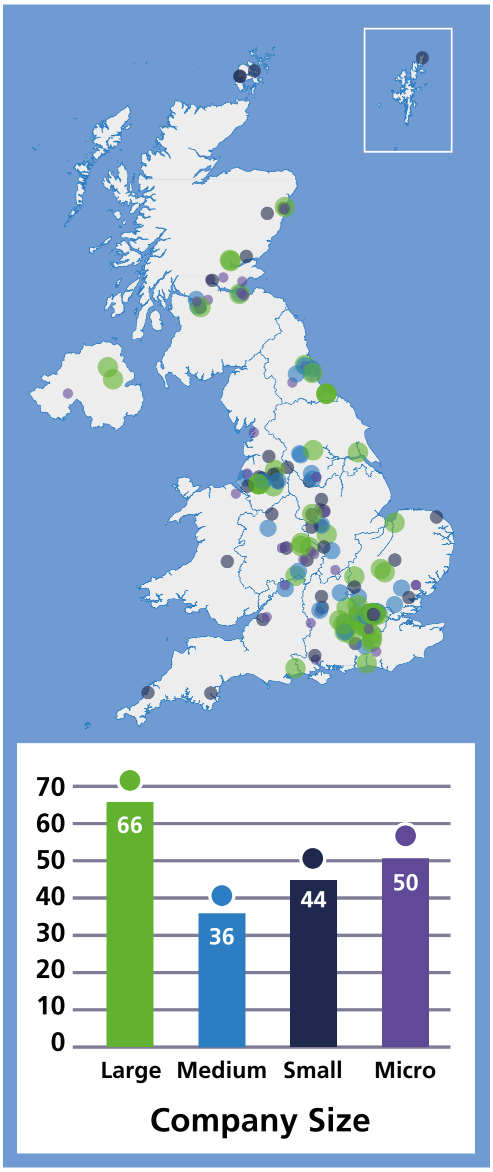


Figure ES1. Locations and sizes of UK hydrogen and fuel cell companies.

The role of universities in the innovation system

Universities underpin the innovation system by developing new knowledge and ideas, enabling knowledge sharing and diffusion, and training skilled researchers. The majority of surveyed companies work with and have a positive view of UK universities. We measured the strength and breadth of UK academia in terms of research activities and publication citations.

The UK has substantial academic expertise across all H2FC research areas and produces world-leading research when measured by average citations. UK academics are globally-connected, with 60% of publications including international authors, but relatively few publications have industrial co-authors compared with competitors such as Japan. The relative focus of the UK on H2FC, relative to other energy technologies, is as strong as its principal competitors. However, academic research funding has declined to a low level, and current UK Government hydrogen energy programmes have little academic involvement. Moreover, a key barrier for our survey respondents was the availability of labour with appropriate skills in the UK, which was considered worse than in competitor countries. UK universities have the expertise to support innovation both through research and training people, but can only carry out this role if appropriate funding is available.

Opportunities and benefits for the UK

One of the major short-term opportunities is to develop heavy-duty vehicles manufacturing. Heavy duty vehicles (HGVs), buses, and potentially taxis, are better suited to fuel cells than batteries at the moment. The UK is already developing fuel cell buses. Public procurement of fleets of fuel cell vehicles might be justified by including the costs of environmental externalities[1] and future cost reductions in business cases. This could underpin the development of fuel cell markets. The creation of a basic national hydrogen refuelling station network would enable the public to use fuel cell vehicles.

In 2017, the UK automotive sector turnover was £85bn, with employment of 856,000. Eighty percent of vehicles were exported. The UK is supporting automotive batteries and electric motors through the Faraday and the Driving the Electric Revolution challenges (£326m in total). Both are components in fuel cell vehicles, and supporting fuel cells would fully future-proof the UK's automotive industry.

The UK is at the cutting edge of understanding the opportunities and challenges of using hydrogen for heating and industry in the longer term. Minimising the cost of producing bulk hydrogen is crucial for these applications. One UK company has a leading autothermal reformer technology to produce "blue" hydrogen from natural gas, with most CO_2 emissions captured by carbon capture and storage (CCS). Another company has a leading electrolyser technology to produce "green" hydrogen from renewables, which is highly flexible and can facilitate the use of hydrogen storage by capturing excess generation. Creating an early market could enable the UK to develop

1 The cost of the damage caused by pollution that is not currently charged to the polluter.

a new export industry for both bulk hydrogen and related technologies.

Actions to encourage hydrogen and fuel cell innovation

The UK has a globally-competitive H2FC sector underpinned by a world-leading science base. It has an opportunity to build on the world leading fuel cell technologies developed by some UK companies, and to take the lead in developing a low-carbon hydrogen economy as an export industry. However, this would require a supportive policy environment. The weak UK market relative to other countries is a barrier to UK companies scaling-up production and reducing costs through innovation. Funding processes for companies are considered slow and excessively bureaucratic, and access to finance is more difficult than in other countries. Academic funding has been reduced to a low level, despite some parts of the H2FC sector experiencing difficulties accessing skilled labour. If UK companies do not have an opportunity to innovate, then they will not be competitive with imports as markets for hydrogen energy develop, in the UK and elsewhere, over the coming decades.

We have identified a number of key actions that could encourage H2FC innovation. These are primarily targeted at the public sector, as public support is required to nurture a domestic market and remove the barriers to innovation identified above.

The actions have three broad goals:

i. to remove barriers and grow UK markets;

ii. to create a strategic vision for hydrogen and fuel cells; and,

iii. to nurture a vibrant innovation ecosystem in the UK.

There will always be some misalignment between UK H2FC growth opportunities, optimal domestic hydrogen end-uses, and industrial and academic comparative advantage. By developing a holistic strategy that acknowledges these trade-offs, and by providing the right support to remove barriers to innovation, the UK has the potential to develop a strong hydrogen and fuel cell industrial sector to meet future energy demands, both at home and abroad.

FOSTERING UK MARKETS

The UK market for fuel cells is very small compared to the global market. A strong domestic market for fuel cells would enable a range of companies to expand their industrial activities and benefit from learning-by-doing and economies of scale. Aside from a handful of demonstration projects, hydrogen is currently only used in industry. The UK has an opportunity to create an early market for low-carbon hydrogen in industry, heat provision, transport, and integration of renewable generation.
We recommend considering four actions to underpin a market:

RECOMMENDATION 1

Use **public procurement, and subsidies** if appropriate, to create a market for fleets of fuel cell vehicles. A good approach would be to identify the best niches, for example for heavy duty vehicles, using business cases that account for the benefits of no air pollution and low noise.

RECOMMENDATION 2

Create a **national refuelling station network** for public and private use. It is difficult to justify the use of fuel cell vehicles if refuelling infrastructure is not available.

RECOMMENDATION 3

Examine opportunities to use **low-carbon hydrogen** in oil refining, ammonia and methanol production, steelmaking, and elsewhere, as part of the new Industrial Strategy Challenge Fund (ISCF) industrial decarbonisation challenge.

RECOMMENDATION 4

Create a **green hydrogen standard scheme** for the UK to enable the value of green and blue hydrogen to be recognised by the market. A standard would use guarantee of origin certificates to demonstrate to customers that they were purchasing low-carbon hydrogen.

A STRATEGIC VISION FOR HYDROGEN AND FUEL CELLS

A coherent strategy is needed to coordinate UK industrial development and innovation funding over the long term, and to introduce a more active engagement process. This strategy could build on the Innovate UK roadmap from 2016, but should ideally treat hydrogen and fuel cells separately, and consider opportunities until 2050. The strategy should balance domestic needs and export opportunities.
We recommend building on the Innovate UK sector roadmap by:

RECOMMENDATION 5

Developing a **hydrogen strategy** to plan for a UK hydrogen economy, and to identify opportunities to export both hydrogen technologies and green hydrogen fuel.

RECOMMENDATION 6

Developing an **electrochemical strategy** covering domestic and export opportunities for battery, fuel cell and electrolyser innovations.

RECOMMENDATION 7

In each strategy, **coordinating innovation funding** from UK Research and Innovation (UKRI) and the UK Government, and how it is best invested between industry and academia, accounting for skills needs in the sector.

RECOMMENDATION 8

Creating a "**Hydrogen Partnership**" to accelerate a shift to hydrogen energy systems in the UK and to stimulate opportunities for UK businesses.

NURTURING A VIBRANT INNOVATION ECOSYSTEM

A strong H2FC sector requires a sufficiently large skilled and innovative workforce, a diverse range of companies that interact both through competition and cooperation. It also requires sufficient funding and other support to underpin R&D, an appropriate regulatory and institutional framework, and demand for products. Successful UK electrochemical companies have already secured substantial foreign direct investment. If the UK can build critical mass and develop a strong knowledge and skills base, then multinationals are likely to invest in R&D in the UK. We recommend four actions:

RECOMMENDATION 9

Studying what would constitute **critical mass** in the hydrogen and fuel cell sectors, in terms of industry and academic capacity, and the skills and knowledge base, and considering whether the UK should invest to create a critical mass.

RECOMMENDATION 10

Consider creating a "**Hydrogen Institute**" focusing on the future use of hydrogen in the energy system, including hydrogen production (excluding electrolysers), storage, safety, combustion, industrial decarbonisation, synthetic fuels production, and pathways for developing hydrogen systems.

RECOMMENDATION 11

Consider creating an "**Electrochemical Institute**" to support fuel cell and electrolyser development, working closely with the Faraday Challenge.

RECOMMENDATION 12

Ensure there are mechanisms for UK researchers and companies to continue and build on **existing collaborations with European counterparts**, and access European markets, given the importance of these to the sector.

CHAPTER 1 - INTRODUCTION

INTRODUCTION

The potential for hydrogen and fuel cell technologies to play an important role in future low-carbon energy systems is being increasingly recognised, particularly for road transport, shipping, industry, and heating buildings. But the scale of future use in hydrogen and fuel cell (H2FC) markets remains very uncertain. At one end of the spectrum, many scenarios envisage a fully-fledged 'hydrogen economy' in which H2FC technologies play key roles in the transport and heat sectors. At the other, H2FC technologies are seen as playing a smaller but still critical role in 'hard-to-abate' sectors such as heavy industry and road freight. Either way, the global market for H2FC technologies is expected to grow significantly.

In recent years, fuel cell vehicles and heating systems have been sold commercially around the world for the first time, and the global market is expected to grow steadily over coming decades. This report examines whether the UK is well placed to develop and secure some of the economic opportunities associated with this market, both in the UK and abroad, as part of the UK Government's focus on clean growth.

1.1 IMPORTANCE OF HYDROGEN

Hydrogen is important because it is one of three key zero-carbon vectors for decarbonising economies in the future, along with electricity and hot water. Studies have identified hydrogen as the most cost-effective option for decarbonising several parts of the UK and global energy systems, as explained in Section 2. One option to produce hydrogen is from electricity using electrolysers. Electrolysers could use excess renewable electricity generation at times of low demand that would otherwise be wasted, which would enable a higher penetration of renewables into the electricity system.

In this report, we refer to hydrogen technologies as those involved in the production, storage, transport, distribution and end-use of low-carbon hydrogen in a decarbonised economy. Hydrogen can be produced with low greenhouse gas emissions from many different energy sources. Many energy processes that combust natural gas could be altered to use hydrogen as a fuel instead. Alternatively, hydrogen-powered fuel cells could replace some of these processes.

At present, virtually all UK hydrogen is used as an industrial feedstock in the chemical industry and in oil refineries. A number of small refuelling stations have been constructed, in several cases with on-site electrolysers, to provide a minimum infrastructure for hydrogen-powered vehicles.

1.2 IMPORTANCE OF FUEL CELLS

Fuel cells convert fuels, including hydrogen, into electricity and heat. Fuel cells are important because they can generate electricity at higher efficiencies than most internal combustion engines. For road transport, this means that they have a higher fuel economy than cars powered by engines. When powered by hydrogen, fuel cells produce no greenhouse gas emissions. The proton-electrolyte membrane (PEM) fuel cells currently used in vehicles operate at low temperatures, so produce negligible air pollutants.

The largest existing market is for combined heat and power (CHP) production in Japanese houses. New markets are emerging for fuel cells such as forklift trucks and drones, but in the future the largest market is expected to be road vehicles. Fuel cells could be used in all road vehicles but are particularly likely to have a role in heavy duty vehicles, such as long-distance trucks and buses, where battery electric powertrains are not practicable. In the transport sector, the demand for hydrogen will probably depend on the competitiveness of fuel cells. For industry and buildings, the potential future market for fuel cells will depend on whether a hydrogen supply is available.

In contrast to other electricity generation technologies, fuel cells generate electricity at high efficiencies even at very small sizes. Although they are electrochemical devices, like batteries, they do not store energy. Electrolysers are closely related to fuel cells, and have many similar technological challenges. Both fuel cells and electrolysers are important technologies because they could have key roles in decarbonising the parts of the energy system in which electrification is either not feasible or provides an inferior service to hydrogen and fuel cells.

1.3 UK´S INDUSTRIAL STRATEGY: A NEW CONTEXT FOR SUPPORTING ENERGY INNOVATION

The UK supports innovation through a variety of funding streams. Innovate UK, the national innovation agency, has supported H2FC technologies for many years. However, in 2017, when launching the industrial strategy, the UK Government commented that "historically, we [the UK] have not been as successful at commercialisation and development as we have been at basic research".[2] The industrial strategy aims to build on UK strengths and extend excellence into the future, and to make the UK one of the most competitive places in the world to start or grow a business. It has the aim of increasing UK productivity by supporting business investment in skills, industries, and infrastructure across the UK, to create high-value jobs. It has five foundations:

1. **Ideas:** the world's most innovative economy.

2. **People:** good jobs and greater earning power for all.

3. **Infrastructure:** a major upgrade to the UK's infrastructure.

4. **Business Environment:** the best place to start and grow a business.

5. **Places:** prosperous communities across the UK.

2 HM Government (2017) Building Our Industrial Strategy.

Low-carbon energy is a major focus of the industrial strategy. “Clean growth”, one of four grand challenges, supports the development, manufacture, and use of low-carbon technologies, systems and services. One of the clean growth missions is to establish the world’s first net-zero carbon industrial cluster by 2040, and at least one low-carbon cluster by 2030, and hydrogen could have a prominent role in acheiving this mission. The mission of the “Future of mobility” grand challenge is to put the UK at the forefront of the design and manufacturing of zero emission vehicles, with all new cars and vans effectively zero emission by 2040. Hydrogen and fuel cells could both have a key role in this mission.

1.4 PURPOSE OF THIS REPORT

Innovate UK published a UK H2FC roadmap in 2016 with a strategy for hydrogen and fuel cells to play a greater role in the UK’s energy mix in the future.[3] A different but complementary approach is taken in this report. We examine potential markets for H2FC technologies in Section 2, both in the UK and abroad, and consider the need for underpinning infrastructure. The UK’s strengths in these technologies are analysed in Section 3 from an innovation system perspective, using a range of statistics including patents, business and academic strengths, and public sector support across the UK. Opportunities for UK businesses are suggested in Section 4, and a series of recommendations to encourage successful innovation are explored in Section 5.

3 E4tech & Element Energy (2016) Hydrogen and Fuel Cells: Opportunities for Growth. A Roadmap for the UK.

CHAPTER 2 - POTENTIAL FUTURE MARKETS FOR HYDROGEN AND FUEL CELLS

INTRODUCTION

Hydrogen already has an important role in the global economy with 70 million tonnes (70 Mt) used each year, primarily as a feedstock for ammonia production and oil refining. The first mass-produced fuel cell cars are now available in a number of countries, and more than 300,000 fuel cells have been fitted to homes in Asia to provide heating and electricity generation. This section examines the potential future role and value of hydrogen, using evidence from a range of studies.

2.1 POTENTIAL ROLE OF HYDROGEN AND FUEL CELLS IN THE UK

The UK Government's Clean Growth Strategy[4] presents three broad UK decarbonisation scenarios that meet the enacted target of reducing UK greenhouse gas emissions in 2050 by 80% relative to 1990. Under the "Hydrogen" pathway, the UK would convert the existing gas network to deliver hydrogen instead of natural gas to many homes and buildings, for heating and cooking, and would predominantly use hydrogen-powered fuel cell cars and vans. Total UK hydrogen production would increase from the current 0.7 Mt to 19 Mt each year by 2050.

In 2015, the Committee on Climate Change (CCC) presented two scenarios.[5] The first, "Full Contribution", showed that hydrogen could decarbonise most heating and transport in the UK. The second, "Critical Path", was based on keeping open the hydrogen option for end-uses that are strategically important, such as for heavy goods vehicles. In 2018, the CCC published a further study that identifies particularly important roles for hydrogen in supplying peak heating on cold winter days, industrial process heat, peak power generation, and for heavy goods vehicles (HGVs) and buses.[6] Total UK hydrogen consumption would increase to around 1.2 Mt in 2030 and to between 3 Mt and 18 Mt by 2050.

> **Total UK hydrogen consumption is expected to increase from 0.7 million tonnes today to 3–19 million tonnes by 2050.**

Since the Paris Agreement set a target of keeping the global temperature rise well below 2°C, there has been growing interest in net zero scenarios, in which all residual UK greenhouse emissions in 2050 are offset by carbon dioxide removal from the atmosphere. In May 2019, the CCC concluded that net zero is necessary, feasible and cost effective for the UK,[7] and the UK Parliament has subsequently accepted a net zero emissions target for 2050. In the CCC's net zero scenario, hydrogen has similar roles as for the 80% greenhouse gas emission reduction in the 2018 report. The deployment of hydrogen technologies is highlighted as a key issue for which progress is too slow at the moment. The Energy Transitions Commission published a

4 UK Government (2018) Clean Growth Strategy
5 CCC (2015) Scenarios for deployment of hydrogen in contributing to meeting carbon budgets and the 2050 target.
6 CCC (2018) Hydrogen in a low-carbon economy.
7 CCC (2019) Net Zero: The UK's contribution to stopping global warming.

report on net zero scenarios in 2018 which proposes hydrogen demand increasing by a factor of 7–11, as one of four key decarbonisation technologies.[8] Hydrogen would be used to decarbonise steel and chemicals, heavy road transport, and shipping. Both of these studies emphasise the need to urgently accelerate the development of hydrogen at scale if the UK is to achieve net zero emissions by 2050, with "low-regrets" deployments over the next decade.

Three broad trends emerge from these scenarios. First, hydrogen is expected to have a substantial role in the future UK energy system, but the nature and hence the size of that role is uncertain. Second, hydrogen is likely to contribute to decarbonisation in several sectors of the economy, fuelling a wide range of technologies including fuel cells. Third, the move to a net zero emissions target has not substantially changed the potential roles for hydrogen in the energy system.

These trends are exemplified in Figure 1, which was produced using the UK TIMES[9] energy systems optimisation model that underpinned the UK Government's Clean Growth Strategy. Three scenarios are shown:

- **Least cost**: an unconstrained least-cost scenario with a net zero greenhouse gas target. In 2050, 3.2 Mt of hydrogen is consumed by industry, HGVs, and for heat decarbonisation.

- **Flexible tech**: a scenario in which all gas distribution networks are converted to deliver hydrogen, and many people use hybrid heat pumps and hybrid vehicles that can be powered by both electricity (when generation costs are low) and hydrogen. Annual hydrogen consumption is 8.9 Mt in 2050.

- **High hydrogen**: a scenario that most closely represents the existing energy system for the public. Most homes and offices continue to be heated by boilers, which are powered by hydrogen rather than natural gas. Most vehicles have fuel cell powertrains that offer a comparable range and refuelling performance to existing petrol vehicles. Annual hydrogen consumption is 19.2 Mt in 2050.

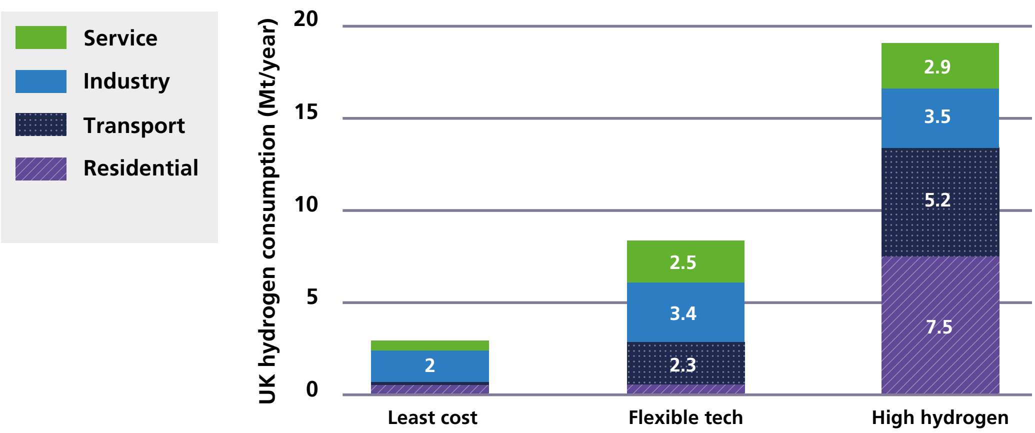


Figure 1. Annual UK hydrogen consumption by sector in 2050, for three scenarios with net zero greenhouse gas emission targets. Source: UK TIMES modelling at University College London.

8 Energy Transitions Commission (2018) Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century.
9 UK TIMES model. https://www.ucl.ac.uk/energy-models/models/uk-times

The move to a net zero target brings both challenges and opportunities for hydrogen. Since emissions from agriculture and municipal landfills are difficult to avoid and must be offset, the mitigation of all energy-related GHG emissions becomes a greater priority. This means that the residual emissions from hydrogen production from natural gas might no longer be economic, unless cost-effective negative emission technologies can be deployed. In the scenarios in Figure 1, steam methane reformer (SMR) with carbon, capture and storage (CCS) is a transition technology, with biomass and low-carbon electricity dominating hydrogen production by 2050. On the other hand, an option not considered in this model would be to use hydrogen and captured carbon dioxide to produce carbon-neutral synthetic hydrocarbon fuels where alternatives are not available (e.g. aviation fuel), and to produce high-value chemicals. These technologies would not be economically viable with an 80% target, but might become viable with a net zero target.

2.1.1 Industry

UK industry currently uses about 0.7 Mt of hydrogen each year as a feedstock for ammonia production, for oil refineries, and in a number of other processes. This is primarily produced from unabated natural gas, but low-carbon production processes could be adopted instead. In the future, hydrogen could be used to produce virgin steel via direct reduction of iron (DRI). Hydrogen could provide high-temperature or medium-temperature heat for cement production and in the chemicals industry. More generally, hydrogen could replace natural gas heating in many industrial processes.

The UK Government has funded a number of decarbonisation feasibility studies in an Industrial Fuel Switching competition. HyNet proposes to develop a hydrogen cluster in North West England in which 10 large industrial sites would be converted to use 100% hydrogen.[10] Other studies are examining the potential for hydrogen to decarbonise cement, glass and calcium lime production.

2.1.2 Hydrogen and fuel cell heating

The UK has an extensive gas network that supplies natural gas to more than 80% of UK homes and to many businesses for heating. Fuel poverty is a key political concern, and one strategy to reduce it is to connect fuel-poor people to gas. However, net CO_2 emissions from gas heating will need to end if the UK is to meet a net zero target.

The HyDeploy project is injecting 20%v/v hydrogen into natural gas streams at Keele University.[11] This approach can reduce CO_2 emissions by up to 6%.[12] It is not practical to increase the hydrogen concentration beyond 20%v/v as this requires the burners on most appliances to be changed. In practice, the limit for some appliances could be lower than 20%v/v.[13] The low emissions reduction means that this approach

10 HyNet project, https://hynet.co.uk/.
11 HyDeploy project, https://hydeploy.co.uk/.
12 20%v/v denotes a gas supply that is 80% natural gas and 20% hydrogen by volume. Since natural gas has a higher energy density than hydrogen at the same gas pressure, hydrogen would only supply 6% of the total energy at this concentration, and hence only 6% of CO_2 emissions could be avoided.
13 Altfeld & Pinchbeck (2013) Admissible hydrogen concentrations in natural gas systems

is only likely to be a temporary measure in the short-to-medium term. The HyNet study proposes injecting 10–20%v/v hydrogen into the gas supply of two million homes and businesses, in addition to fully converting nearby industrial sites.[14]

In recent years, there has been much interest in converting the gas networks to deliver 100% low-carbon hydrogen instead of natural gas. This strategy would take advantage of the UK's existing gas delivery infrastructure, as the plastic gas pipes that are being deployed by the multi-decadal Iron Mains Replacement Programme are suitable for transporting hydrogen. It offers a low-carbon "business-as-usual" option for consumers, who could use hydrogen boilers and cookers that would provide a similar quality of service to existing appliances with minimum disruption. Moreover, since a key part of the UK Government's approach to reducing fuel poverty is to connect homes to the gas networks, it might be considered politically unfeasible to remove access to gas in the future in order to decarbonise heating. It might, however, be considered politically feasible to convert the supplied gas to hydrogen.

In 2016, Northern Gas Networks published an engineering assessment of converting the city of Leeds to hydrogen,[15] and expanded this to the whole North of England region in 2018. They did not identify any technical issues that would prevent conversion. They proposed a range of further engineering tests and studies on the gas networks and end-use appliances in order to confirm that hydrogen would be a safe and economic fuel. The H21 Phase 2 Network Operations[16] and Hy4Heat[17] programmes have been funded by Ofgem and the UK Government, respectively, to explore the technical feasibility upstream and downstream of the meter.

Reports for the CCC[18] and the National Infrastructure Commission[19] concluded that a hydrogen for heating strategy could deliver heating at a similar cost to an electrification strategy focusing on heat pumps. In contrast, a study for the Energy Networks Association concluded that the cost of an electrification strategy could be up to three times higher.[20] At present, there is much uncertainty over the best long-term option, or mix of options.

> **Hydrogen could heat homes at a similar cost to heat pumps.**

Although the potential for fuel cells to power transport has received the most attention historically, micro-combined heat and power (CHP) fuel cells in Japan and to some extent in Korea are by far the largest existing market for fuel cells. These markets provide both electricity generation and heating within houses. Ceres Power, a UK SME, has produced a world-class micro-CHP fuel cell, as discussed in Section 3.2.2. There is evidence that deploying fuel cell micro-CHP in the UK would also

14 Cadent (2018) HyNet North West: From Vision to Reality.
15 Northern Gas Networks (2016) H21 Leeds City Gate.
16 H21 Phase 2 Network Operations.
17 Hy4Heat, https://www.hy4heat.info/.
18 Strbac G. et al. (2018) Analysis of Alternative UK Heat Decarbonisation Pathways.
19 Element Energy & E4tech (2018) Cost analysis of future heat infrastructure options.
20 KPMG (2016) 2050 Energy Scenarios: The UK Gas Networks role in a 2050 whole energy system.

facilitate electrification of heating in other houses.[21] Although the CCC considered micro-CHP to be too expensive relative to hydrogen boilers and hybrid heat pumps,[22] modelling presented in Figure 1 identified a role in up to 10% of UK homes. The relative competitiveness of each heat technology is sensitive to the assumed future market size and capital cost, and also the modelled heat load and the value of the electricity generated by the micro-CHP fuel cell.

2.1.3 Road transport

Long-haul heavy goods vehicles and buses are not well suited to battery electric powertrains[23] due to:

i. battery weight (which reduces the payload);

ii. battery cost;

iii. limited range on a single charge; and,

iv. high power requirements for rapid charging of large batteries. Heavy-duty vehicles are considered key sectors for fuel cell vehicles, with Nikola, a USA-based start-up, developing a hydrogen truck with a range of 500–1,000 miles and a 15-minute refuelling time.

> **Hydrogen-powered fuel cells are ideal low-carbon powertrains for heavy-duty vehicles.**

Battery powertrains have dominated the discourse for cars and other smaller vehicles over the last few years, with numerous hybrid, plug-in hybrid and pure electric models being launched in the UK.[24] This is reflected in the UK Government's transport decarbonisation policy paper, which solely considers electrification.[25] Yet pure electric powertrains, with the lowest emissions, have achieved less than 1% of new UK car registrations over the last five years (Figure 2). Two barriers to using pure electric vehicles for many consumers are an inadequate driving range and a lack of public charging facilities. A study found that a range of 200 miles would be required for 50% of consumers to choose a pure electric vehicle as their main car.[26] Reductions in battery prices might increase take-up, and range has improved over time, but major

21 EPSRC H2FC Supergen Hub (2014) The role of Hydrogen and Fuel Cells in Providing Affordable, Secure Low-carbon Heat.
22 CCC (2018) Hydrogen in a low-carbon economy.
23 The powertrain is the vehicle mechanism that converts the engine's power into movement – so is composed of the engine, transmission, driveshaft, differentials and axles.
24 Hybrid vehicles have small batteries that charge through regenerative breaking and from a conventional petrol engine. Plug-in hybrid vehicles have a larger battery capacity that can be charged by mains electricity while stationary, and can travel short journeys purely using electricity. Pure electric vehicles do not have conventional engines.
25 DfT (2020) Decarbonising transport: Setting the challenge
26 TRL et al. (2019) Consumer Uptake Trial Report: Mainstream consumers' attitudes and willingness to adopt BEVs and PHEVs.

improvements in battery technology would be needed to greatly extend the range or decreasing the refuelling time. At the moment, pure electric vehicles are still in the early adopter phase and hybrid vehicles are more popular.

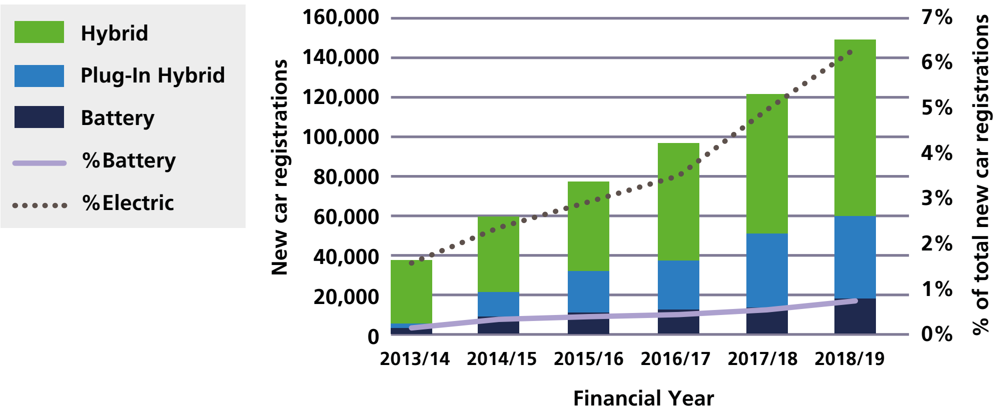


Figure 2. Registration of new electric cars in the UK by financial year. Source: SMMT data.

The development of commercial fuel cell cars has lagged behind pure electric cars. The first model was launched in 2013, in Asia. Fuel cell vehicles are also electric vehicles: all are hybrids, with the fuel cell charging the batteries or directly powering the electric motor. Their principal difference compared to pure electric vehicles is most of the batteries are replaced with a fuel cell stack and a hydrogen tank. An advantage of fuel cells is that the materials are easier to recycle than batteries. However, fuel cells tend to be less efficient than battery vehicles (Box 1). From a customer's perspective, fuel cell vehicles offer a similar experience to conventional vehicles, with a similar range and refuelling time. Improvements in battery and motor technologies will assist both pure electric and fuel cell vehicles. However, the expansion of a market for fuel cell vehicles has been inhibited by the availability of only a few models, high initial purchase prices, and a very limited hydrogen refuelling infrastructure.

The UK Government has prohibited the sale of new non-hybrid petrol and diesel cars from 2040, and is currently consulting on bringing forward this date to 2035, or earlier, and also prohibiting petrol and diesel hybrid vehicles from 2035. The market needs to change completely over the

1 Are fuel cell vehicles substantially less efficient than battery vehicles?

One argument that is often made in favour of battery vehicles is that they are much more energy efficient than fuel cell vehicles. This argument invariably compares the powertrain efficiency (kWh/kWh), which measures the useful motive energy derived from the original energy source, and is much higher for battery vehicles than fuel cell vehicles that use hydrogen from electrolysis.

A more useful measure, however, is the vehicle efficiency (kWh/km), which depends on the weight of the car. Battery vehicles become increasingly heavier as the number of batteries is increased to extend the range, so their vehicle efficiency is very sensitive to their range. Current battery vehicles have much shorter ranges than their fuel cell equivalents. If the battery vehicle range were increased to compare vehicles with the same range, then the difference in efficiency would be smaller than that suggested by the powertrain efficiency comparison.

next 15–20 years in order to meet these targets. It is very difficult to identify which powertrains will be the most competitive in the long term. As ultra-low emission vehicles (ULEVs) reduce in price, petrol and diesel powertrains are likely to become increasingly socially unacceptable due to their emissions of both greenhouse gases and other air pollutants. An example from recent years is the substantial reduction in the registration of new diesel cars due to air pollution concerns. Despite pure electric vehicles being available for a number of years, it is not clear whether they have attained a strong first-mover advantage (see Figure 2).

> **It is very difficult to identify which car powertrains will be the most competitive in the long-term.**

Although many automobile manufacturers have concentrated their R&D programmes on pure electric rather than fuel cell vehicles, a recent survey found that 79% of automotive directors believe that fuel cell vehicles will be the real breakthrough for electric mobility.[27] The same survey forecast roughly equal shares of the market for conventional, hybrid, pure electric, and fuel cell powertrains in 2040. This is consistent with long-term cost of ownership projections that suggest a similar cost for all four powertrains as the costs of new technologies reduce.[28] The uncertainties in these cost projections are higher than the differences between them, so identifying the most economical technology is not feasible at present.

This uncertainty is amplified by potential changes in the use of mobility by the UK population in the future. A UK Government Foresight report identifies the impacts of electrification and vehicle automation as key future drivers of demand.[29] Automation could enable many young and old people to access mobility at more affordable prices, as there would be no need for a driver, while making greater use of a smaller fleet of vehicles. This would favour electric powertrains with higher capital and lower operating costs.

27 KPMG (2019) Global Automotive Executive Survey 2019.
28 Dodds P. & Ekins P. (2014) A portfolio of powertrains for the UK: An energy systems analysis.
29 Government Office for Science (2019) Future of Mobility.

2.1.4 Other transport (rail, marine and aviation)

There is increasing interest in decarbonising parts of the rail network using fuel cell trains. Compared to diesel equivalents, fuel cell trains are smoother, quieter, more efficient, and should be easier and cheaper to maintain.[30] While more expensive than diesel and electric trains, they are cheaper than electrifying a line, less vulnerable to extreme weather events that particularly affect electric trains through overhead or third rail damage, and have no electrocution hazard. Moreover, on partially electrified lines such as the East Coast Mainline, fuel cell trains could use the same electric motors on the electrified and non-electrified sections, and would only operate on hydrogen on the non-electrified sections.

The cost of low-carbon fuels is considered a major barrier to decarbonising international shipping. Hydrogen, and ammonia and methanol produced from low-carbon hydrogen, are considered potential replacements for heavy oils in the UK Government's Clean Maritime Plan.[31] Many ports have poor air quality and adopting either of these low-carbon fuels would greatly reduce air pollutant emissions. For this reason, ferries that sail near populated areas are an early potential market for hydrogen. As a first step, the Innovate UK HyDIME project is converting an Orkney ferry to inject low-carbon hydrogen into the diesel fuel stream, which will reduce the greenhouse gas emissions from the ferry by around 50%.[32]

> **Hydrogen is a decarbonisation option for non-electrified rail, shipping, and possibly even short-range aeroplanes.**

Aircraft are particularly challenging to decarbonise because fuel with a high specific energy is required to power long-distance flights. Hydrogen-powered fuel cells have been proposed for flights over shorter distances. The UK HyFlyer project is converting a six-seater aircraft to use fuel cells as a demonstration project.[33] Unmanned aerial vehicles are another developing market for fuel cells.

2.2 INTERNATIONAL MARKETS FOR H2FC TECHNOLOGIES

Hydrogen has been used as an industrial feedstock for decades. There is an opportunity to decarbonise this hydrogen, and potentially to also use excess production capacity as a source of hydrogen for emerging markets. Most H2FC markets are niches or are emerging with public support:

- Fuel cell micro-CHP in Japan and Korea, with more than 300,000 units deployed.
- Emergency power supplies.
- Forklift trucks in warehouses, particularly in the USA.

30 E4tech (2018) The Fuel Cell Industry Review 2018.
31 DfT (2019) Clean Maritime Plan.
32 HyDIME project, https://hydime.co.uk/.
33 HyFlyer project, https://www.emec.org.uk/projects/hydrogen-projects/hyflyer/.

- Heavy goods vehicles in the USA.
- Cars in Asia and the USA.
- Unmanned aerial vehicles (UAVs).

These existing markets are primarily driven by demand for fuel cells, rather than hydrogen. A hydrogen supply is needed, but it is not always low-carbon at the moment. Although studies have suggested an important role for bulk hydrogen to decarbonise parts of the global energy system, there are not yet any markets for bulk low-carbon hydrogen.

> **A range of markets for fuel cells are emerging around the world.**

There is some optimism in the H2FC community that markets could greatly increase in size in the coming years. A Hydrogen Europe roadmap for the EU identifies a €130bn industry for the fuel and associated equipment for EU companies by 2030, reaching €820bn by 2050.[34] The Energy Transitions Commission have suggested that global consumption could increase to 425–650 Mt by mid-century, even if fuel cell cars and vans only have a small role.[35] The Hydrogen Council, a grouping of more than 80 industrial company CEOs, have set out a vision in which global consumption would reach 550 Mt, with hydrogen used across transport, industry, building heat, and electricity generation.[36] They have identified 22 hydrogen applications that may become the most cost-competitive low-carbon solution by 2030. This includes heavy duty vehicles, electricity generation, heating where gas network conversion is feasible, and also in some heavy industries. This global analysis is consistent with the potential roles identified for the UK in Section 2.1.

Although the International Energy Agency (IEA) has historically focused on electrification as the principal decarbonisation strategy, they published a paper on hydrogen and ammonia production from low-cost renewable generation in 2017.[37] In June 2019, in preparation for a meeting of energy ministers at the G20 summit in Japan, the IEA published a major report on the potential for hydrogen to contribute to global decarbonisation.[38]

34 FCH JU (2019) Hydrogen Roadmap Europe.
35 Energy Transitions Commission (2018) Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century
36 Hydrogen Council (2017) Hydrogen scaling up: A sustainable pathway for the global energy transition.
37 Philibert C. (2017) Producing ammonia and fertilizers: new opportunities from renewables.
38 IEA (2019) The Future of Hydrogen: Seizing today's opportunities.

2.3 HYDROGEN INFRASTRUCTURE NEEDS

The emergence of a market for hydrogen vehicles in the UK is in part hindered by the lack of production and delivery infrastructure.

2.3.1 Hydrogen production

Hydrogen can be produced from a range of fuels including electricity, natural gas, coal, oil, and biomass. Natural gas reforming is the cheapest and most widely-used technology at present, but emits substantial CO_2 emissions to the atmosphere. Low-carbon hydrogen could only be produced from fossil fuels if most or all of the CO_2 emissions were captured and sequestered by a carbon capture and storage (CCS) system. Such low-carbon hydrogen from fossil fuels is called "blue" hydrogen.

With renewable generation costs reducing, and the net zero emissions target adopted, the CCC and others have instead proposed producing "green" hydrogen using renewable electricity.[39]

Hydrogen could facilitate the development of renewable electricity generation through power-to-gas, in which hydrogen is produced by highly responsive electrolysers at times of high renewable generation and low electricity demand.

> **Hydrogen can be produced from renewable electricity or from a range of fuels when using carbon capture and storage.**

For fuel cell vehicles, the total cost of ownership is dominated by capital and operating costs, rather than fuel costs. In contrast, where hydrogen is used for decarbonising heating, industry, and electricity generation, overall costs are very sensitive to the hydrogen cost. A key challenge for using hydrogen in these sectors is to reduce the cost of hydrogen. Table 1 shows that there is much uncertainty about the future cost of bulk hydrogen, with one estimate even projecting cheaper green hydrogen than natural gas by 2050 in some countries (but probably not the UK). The uncertainty is caused by the sensitivity of the cost to the production method, the electricity, gas or biomass feedstock price, the carbon price, and also the season if a peak hydrogen demand for space heating were to develop in the future. At forecast UK prices, the value of hydrogen in the UK in 2050 would be in the range £4bn–£28bn, while the global market value would be at least £380bn.

39 CCC (2019) Net Zero: The UK's contribution to stopping global warming; Energy Transitions Commission (2018) Mission Possible: Reaching net-zero carbon emissions from harder-to-abate sectors by mid-century.

Source	Average £/MWh	Range £/MWh	Notes
CCC hydrogen[40]	38	28-44	Range reflects the hydrogen production method
BNEF hydrogen[41]	19		Reducing from 39 £/MWh in 2030. £=1.3$
UK TIMES hydrogen[42]	56	43-119	Range reflects seasonal hydrogen cost variations
Natural gas	20		Increases to 24 £/MWh if the Climate Change Levy in 2020 is included in the price

Table 1. Projections of the cost of delivered hydrogen at scale in 2050, compared to natural gas (£/MWh). *CCC and BNEF costs are projections from the Committee on Climate Change and Bloomberg New Energy Finance, respectively. UK TIMES costs are shadow commodity prices from the UK TIMES model scenarios in Figure 1. Natural gas costs assume an average price for industry of 2 p/kWh, based on statistics for the last two years from the UK Government.*

2.3.2 Hydrogen delivery infrastructure

Hydrogen can be delivered as a gas or a liquid, or produced at the point of use using small, decentralised electrolysers or gas reformers.[43] Figure 3 summarises the various infrastructure options. Large-scale infrastructure is more cost-effective per unit of delivered hydrogen than small-scale infrastructure, but the high capital cost presents a substantial risk to investors if expected demand does not materialise. Since hydrogen demand for road transport is likely to grow slowly, refuelling infrastructure is likely to be decentralised at first. However, if major industrial clusters or cities were converted to use hydrogen, then the large and immediate hydrogen demand would facilitate the deployment of large-scale pipeline distribution infrastructure, which could also aid the development of hydrogen-powered road transport.

40 Hemsley M. (2020) Hydrogen in a Net-Zero economy. Seminar to the UK Hydrogen and Fuel Cell Association, 29 January 2020.

41 BloombergNEF (2020) Hydrogen Economy Outlook.

42 BEIS (2019) Prices of fuels purchased by manufacturing industry, Table QEP 3.1.1. BEIS (2016) Climate Change Levy Rates.

43 Since CO_2 emissions from small gas reformers at refuelling stations would be too small to justify a dedicated CCS system, it is likely that gas reformers would be at best a transition technology.

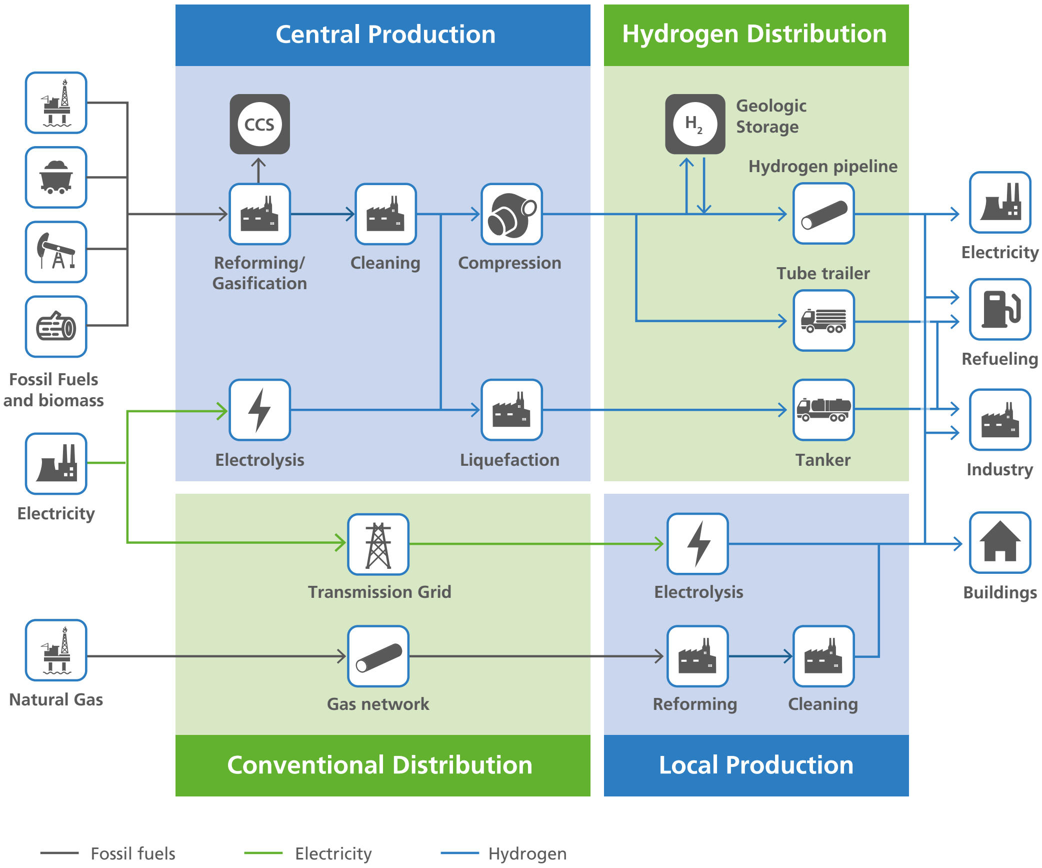


Figure 3. Hydrogen infrastructure options. Source: EPSRC H2FC Supergen Hub.[44]

2.4 HYDROGEN VALUE CHAINS

The wide variety of hydrogen production, delivery, and end-use technologies means that there are many potential value chains, both in the UK and abroad, which could offer opportunities for UK businesses. It is useful to distinguish between fuel and technology value chains.

The value chain for fuel is composed of the hydrogen production and delivery infrastructure shown in Figure 3, together with the feedstocks and associated professional services (e.g. engineers, lawyers, accountants, etc.). Some value would be captured due to the infrastructure being located in the UK. Since the UK is considered to have a greater renewable generation resource than most European countries, there could also be an opportunity to develop an internationally-competitive green hydrogen export industry in the longer term.

Many parts of the fuel value chain, and end-use technologies in particular, contain a range of high-value components and materials. For example, in addition to manufacturing electrolysers and fuel cells, UK industry has opportunities to develop and manufacture high-value catalysts, membranes, and balance-of-plant equipment, and to add value through systems integration, project management, and other

44 EPSRC H2FC Supergen Hub (2017) The role of hydrogen and fuel cells in future energy systems.

services. Each of the many H2FC technologies is associated with a technology value chain, and there are opportunities to create value from all or parts of those chains. The UK already has substantial interests in some industries that H2FC technologies might replace, including vehicle, engine, and boiler manufacturing – including jobs that may be vulnerable as the transition to a low-carbon economy unfolds.

CHAPTER 3 - THE UK'S STRENGTHS IN EMERGING HYDROGEN AND FUEL CELL VALUE CHAINS

INTRODUCTION

An innovation system perspective identifies the strengths and position of the UK to benefit from globally emerging H2FC supply chains. Innovation success in new and emerging technology areas requires a successful network of companies, a growing scientific, technical and market-related knowledge base, resources, and a nurturing business environment.

To inform our analysis, we identified and examined the activities of 196 businesses that are actively working with H2FC technologies in the UK. We sent each business a survey with questions about their operations and their views of innovation in the UK (Box 2). We also compiled innovation funding, patent, and journal publication statistics. This section presents a series of metrics and other insights from this evidence base.

2 Survey of UK-Based companies

We surveyed 196 companies with H2FC activities in the UK and received responses from 32 businesses. Our respondents cover the full supply chain, including both specialist H2FC companies and larger companies with small investments in H2FC. Most are UK companies, rather than subsidiaries, and they are distributed across the UK.

While the sample cannot be seen as representative of all companies in the sector, it provides some useful insights into the experiences and needs of a subset of H2FC companies.

3.1 THE EMERGING UK H2FC SECTOR: COMPANIES, ENTREPRENEURSHIP AND THE SUPPLY CHAIN

One third are large companies, in many cases multinationals. There are also 36 medium, 44 small, and 50 micro-sized companies. While large companies tend to have minor H2FC interests, the micro companies, which are often spin-offs from universities or small engineering consultancies, primarily focus on H2FC. The large number of businesses offers opportunities for networking. Nurturing a positive business environment for such a range of companies could be done through a range of tailored approaches.

Companies work across a wide range of areas, with the largest being consulting and engineering services, transport, fuel cell manufacturing, production of hydrogen, ancillary equipment, and materials (Figure 4). The activities of most of these companies are directly or indirectly related to fuel cells, the focus of existing H2FC markets, rather than bulk hydrogen.

> **We identified 196 companies that operate across the hydrogen and fuel cell supply chain in the UK.**

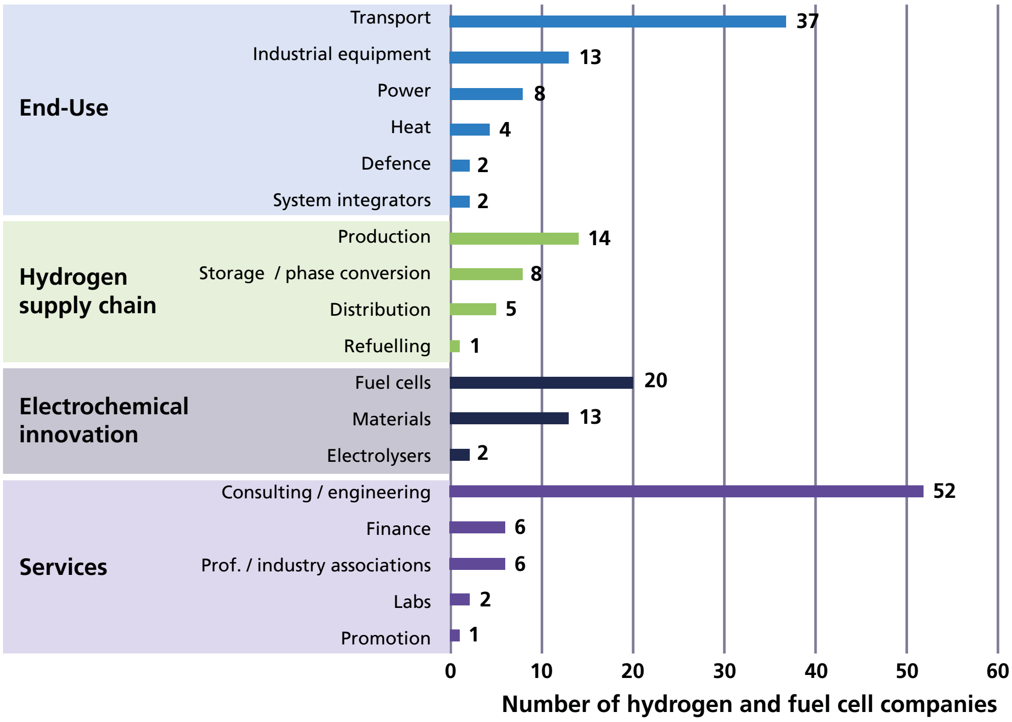


Figure 4. Number of businesses specialising in each H2FC area in the UK. Source: Analysis of the primary activities of the 196 H2FC businesses identified by this study.

Most companies with H2FC interests operate in the end-use market (35%) or provide business-to-business services (34%). Vehicle manufacturers and transportation companies in the automotive sector dominate the end-use market. Despite the wide use of fuel cells in Asia and the focus on hydrogen for heating in the UK, only eight companies supply fuel cells for heating or power and only four provide installation services. While there is a growing interest in using hydrogen pathways to decarbonise industry in the EU,[45] and an ambition to develop a net-zero industrial cluster in the UK by 2040, projects are only at the engineering design stage and there is no market as yet. Fuel cells and materials are the focus of most companies working on technology development.

Consulting and engineering companies comprise the largest group of companies providing business-to-business services. Around 60% are micro or small businesses. Two companies provide engineering integration for auxiliary power units (for servers, CCTV, or lighting). Two companies focus on testing H2FC devices, and the publicly-funded Hydrogen and Safety Executive (HSE) and National Physical Laboratory (NPL) also work in this area.

The UK has one of the most successful electrolyser manufacturers in Europe (ITM Power), and leaders in fuel cell technology (Ceres Power; Intelligent Energy) and materials development (Johnson Matthey). However, although 20 companies develop fuel cells and another 13 develop materials (e.g. catalysts; membranes), manufacturing is the focus of fewer than 20% of H2FC companies.

45 DG Research and Innovation (2018) Final Report of the High-Level Panel of the European Decarbonisation Pathways Initiative.

Only 14% of the businesses work directly on the hydrogen fuel supply chain. Producing hydrogen is the focus of 14 companies, either for resale, for auto consumption, for industrial processes, or as a by-product. Most UK refuelling stations include a partnership between a company that supplies the technology that produces hydrogen (e.g. ITM Power), a refuelling station owner (e.g. Shell) and a hydrogen consumer (e.g. Heathrow Airport; Honda). The storage/conversion businesses mainly manufacture hydrogen cylinders and cryogenic systems, with one providing a solid-state hydrogen storage solution. There are a number of wholesalers supplying industrial equipment (e.g. valves) to industrial customers that use conventional hydrogen as a feedstock in their plants. Many oil and gas wholesalers could transition from natural gas auxiliary equipment and supplies to hydrogen, and 13 already target the H2FC market.

3.2 CASE STUDIES OF UK H2FC BUSINESSES

ITM Power and Ceres Power are UK start-ups that have been successful at fundraising equity and partnering with global companies. Both have considerable back orders and revenues. However, neither has generated net profits to date. In contrast, Johnson Matthey is a FTSE100 technology company with a long-standing, profitable fuel cell division. It is one of the world leaders in materials development and hydrogen production technologies.[46] All three companies have substantial R&D programmes in the UK that have been underpinned by substantial public financial support.

3.2.1 ITM Power

ITM Power was founded in 2001 and specialises in the manufacture of integrated hydrogen energy supply systems, and particularly electrolysers. The company headquarters are located in Sheffield, with representation in Germany, France, USA, and Canada. ITM has projects under contract or in the final stages of negotiation worth over £35m.

ITM has received a range of EU and UK grants to improve and deploy their technologies, which have sustained their research in the absence of a commercial market.[47] Around 75% of their income is from projects (£17.5m) and 25% from sales revenue (£4.6m). The company has been very successful at raising funds and its partners or customers include Sumitomo, National Grid, Cadent, Northern Gas Networks, RWE, Engie, BOC Linde, Toyota, Honda, Hyundai, Anglo American, and JCB. Although sales are growing, the company is still transitioning from grants to sales to make the business sustainable in the long term. It invests around half of sales revenues in research – £2.3m in 2019 – and has struggled to be profitable. To facilitate growth, ITM is building a new factory with an annual electrolyser manufacturing capacity of 1 GW.

46 Financial details for these case studies have been obtained from the corporative websites of the companies reported.

47 ITM Power are part of the HPEM2GAS, REFHYNE and eLYOFF projects, which have received €21m funding in total from the EU, and are also part of the £6.8m UK HyDeploy project.

ITM owns 13 patents on polymer membranes and PEM electrolyser manufacturing. The company protects its Intellectual Property (IP) primarily in the USA market. The company owns eight hydrogen refuelling stations in the UK and it has contracts with the Metropolitan Police and with Green Tomato Cars to supply hydrogen. It also offers turnkey solutions to other parties and it is currently involved in the construction of another six refuelling stations. It has recently agreed a joint venture with Linde, a German industrial chemical company, in which Linde has taken a 25% equity stake.[48] This is targeting the industrial hydrogen market and will supply a 10 MW PEM electrolyser to a Shell oil refinery in Germany.

3.2.2 Ceres Power

Ceres Power creates and licenses IP related to the design and manufacture of solid oxide fuel cells. Applications include micro-CHP, commercial CHP, grid-scale electricity generation, and vehicle range extenders. Its key technology is a revolutionary low-temperature materials technology and steel stack design, which is cheaper to produce than alternatives. Ceres is a spin-out from Imperial College and has around 300 employees. It invests heavily in innovation, with R&D costs for the 2019 financial year (£13.8m) similar to revenues (£15.3m). Ceres has recently expanded its technology focus to include electrolysis and e-fuels through the same business model.

Ceres was part of Ene.Field, a €53m EU project that deployed 1,000 residential micro-CHP fuel cells across 11 EU states.[49] In 2013, Ceres adopted an asset-light licensing business model in which they partner with major players in the industry to enable product development and grow manufacturing capacity. Those partners include Bosch, Weichai, Honda, Miura Co and Doosan, and they have started to operate in the Chinese, German, Japanese, Korean and USA markets. Bosch and Weichai Power have also made a total equity injection of over £95m between them. This model allows the deployment of technology at a pace and scale that would not be possible for an emergent product development and manufacturing company. Ceres has orders and pipeline for £79m through engineering services, technology transfers, and licensing schemes and royalties. Losses decreased from £10m in 2018 to £4.8m in 2019, despite an investment of £8m in a new manufacturing facility in the UK that is expected to commence operations in 2020.

CERES owns more than 40 single family patents, which mainly focus on manufacturing methods to deposit electrolyte materials (ceramic) on a metallic substrate for solid oxide fuel cells.

3.2.3 Johnson Matthey

Johnson Matthey is a 200-year-old multinational company. It has extensive experience in hydrogen production process technologies and offers a wide range of catalysts and other materials for desulphurisation, pre-reforming, steam reforming and water-gas shift reactions. It also has important expertise in precious metals

48 Joint venture with Linde AG and £38M strategic investment
49 Hydrogen Europe (2019). Members.

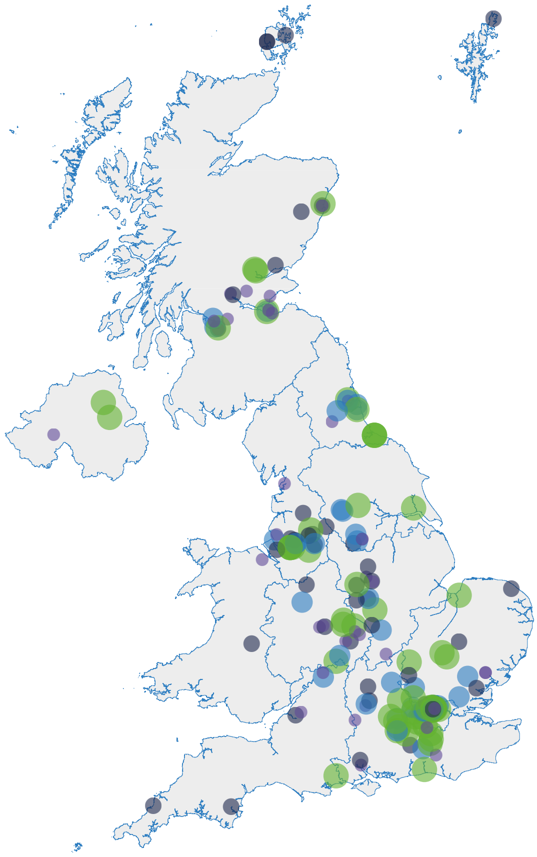
handling and refining.

Johnson Matthey Fuel Cells was created in 2000 to manufacture fuel cell components such as membrane electrode assemblies (MEAs), catalyst coated membranes, and fuel cell catalysts for portable, automotive, and stationary applications. Their manufacturing facility in Swindon was the world's first dedicated MEA production facility for PEM fuel cells. Their R&D capability for fuel cells is located in the UK. They own more than 15 patents directly related to H2FC technologies. Fuel cell division sales in 2016/2017 were £11m worldwide; however, this area of the business still generated an operating loss. In 2017/2018 sales of fuel cells products grew by over 50%, helped by increased volumes to stationary applications, and the division delivered an operating profit.

Johnson Matthey have participated in 19 EU-funded projects worth a total of €90m across all aspects of hydrogen generation, storage and use. Using UK Government funding, they are working with partners to demonstrate a gas heater reformer technology to produce "blue" hydrogen.

3.3 PLACE: H2FC BUSINESSES OPERATE ACROSS THE UK

The locations of companies with commercial H2FC activities are shown in Figure 5. Locations are broadly in proportion to economic activity and population, with activities in all regions and little evidence of strong geographic clustering.



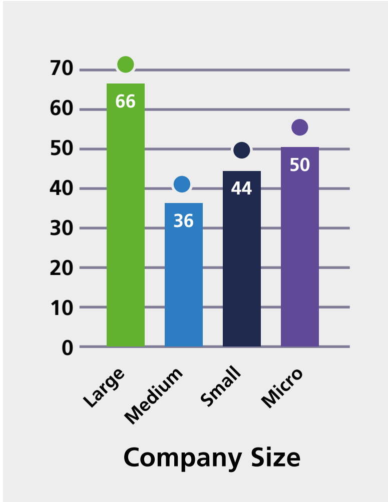


Figure 5. Map of UK businesses with commercial H2FC activities, by company size.

The industrial strategy aims to promote economic development across the UK. Figure 6 analyses geographic patterns of public grants for innovation-related projects (i.e. excluding pure academic research), funded by Innovate UK and Horizon 2020, to see if this goal is reflected by historical public support for H2FC. It does not include funding from the European Regional Development Fund, the Engineering and Physical Sciences Research Council (EPSRC), Ofgem, and the Department for Business, Energy & Industrial Strategy (BEIS), as information about the regional breakdowns of funding for H2FC are not available. London and South East England have the highest number of supported companies. Yorkshire & Humberside and the East Midlands have received substantial support. The economies of these regions typically see lower-than-average rates of R&D intensity, and have lower-than-average productivity levels, suggesting H2FC investments are playing a role in regional re-balancing. However, the strong H2FC performance of these regions is based on a narrow pool of companies, in particular Intelligent Energy (in Loughborough) and ITM Power (in Sheffield). Other regions that have been less active in terms of overall grant-funded R&D activity have a broader pool of relevant expertise.

In particular, East England, South East of England, and London are home to a large number of specialised knowledge-intensive companies that are involved in the H2FC supply chain.

> **Hydrogen and fuel cell businesses have operations across the UK.**

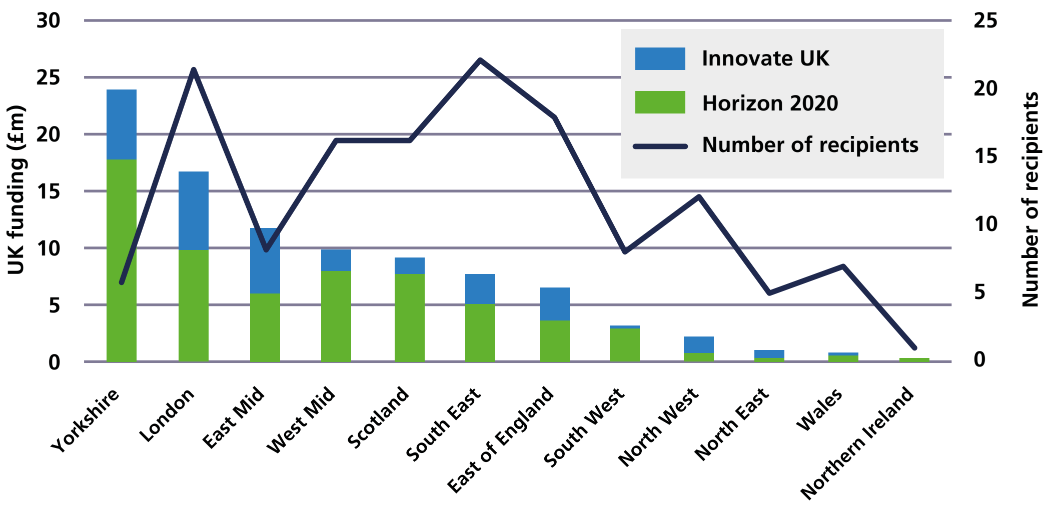


Figure 6. Geographical breakdown of Horizon 2020 and Innovate UK funding for H2FC over the lifetimes of the two programmes. *Source: Analysis of Innovate UK and Horizon 2020 data. The figures for some regions include substantial support for fuel cell electric vehicle users in demonstration trials. This significantly uplifts the total values in London, South East England, the West Midlands and Scotland in particular. Most projects involve a number of partners, and the grant to each partner is recorded in the region where that partner has a head office. This graph excludes co-funding provided by the company from other sources. It does not consider H2FC funding received from the European Regional Development Fund, EPSRC, or the UK Government.*

There is increasing interest in decarbonising industry and heat using bulk hydrogen, as explained in Sections 2.1.1 and 2.1.2. While the initial focus of these schemes has been on Yorkshire, the North West, the North East, and Wales, where much heavy industry is located, it is notable that relatively few companies in these regions have received Innovate UK or Horizon 2020 public support. There is potentially an opportunity to develop hydrogen expertise in these regions, which could support the use of hydrogen in industry and enable the regions to capture as much value as possible from the hydrogen supply chain.

There are UK (UKHFCA), Scottish (SHFCA), and Welsh hydrogen trade associations, and two regional networks (Hydrogen London and the Midlands Fuel Cell and Hydrogen Network). The creation of more focused industry associations, for example on hydrogen for heating, was recommended for consideration by the Innovate UK H2FC Roadmap in 2016.[50] This has not yet happened, outside of the BEIS Hy4Heat project stakeholders, and would be difficult to justify in the absence of a market.

50 E4tech and Element Energy (2016) Hydrogen and Fuel Cells: Opportunities for Growth.

3.4 THE KNOWLEDGE BASE: EXPLORING THE UK'S TECHNOLOGICAL AND SCIENTIFIC CAPABILITIES IN H2FC TECHNOLOGIES

The knowledge base can be described in terms of the quantity of H2FC patents, the breadth of the science base in universities, and the quantity of H2FC research outputs that the UK produces. This section compares the UK against competitors using these metrics.

3.4.1 GENERATING INVENTIONS: INSIGHTS FROM PATENT ANALYSIS

Patents can help us to understand the relative technological capabilities of UK-based companies in the area of H2FC technologies. Patents are well known to be an imperfect measure of innovation: many good ideas are never patented, and many patented inventions turn out to be commercially irrelevant. Nevertheless, patenting rates do correlate well with many other indicators of innovative activity, as well as share value growth. For a technology-based sector like H2FC, they provide a useful lens on the relative performance of the UK.

Almost half of all H2FC patents (around 17,000 in total) were published in the past 10 years. We have restricted our analysis to this period and have also only considered patents of higher quality.[51] Figure 7 illustrates the ranking over time of leading countries in terms of the number of patents filed. The UK has been consistently within the top ten globally, but is still an order of magnitude behind Japan and the USA. Japan has led H2FC patenting, followed by the USA, with recent strong growth from South Korea. This is consistent with recent policy support from the South Korean government, which has emphasised an ambitious role for H2FC technologies in their future industrial and energy strategies.

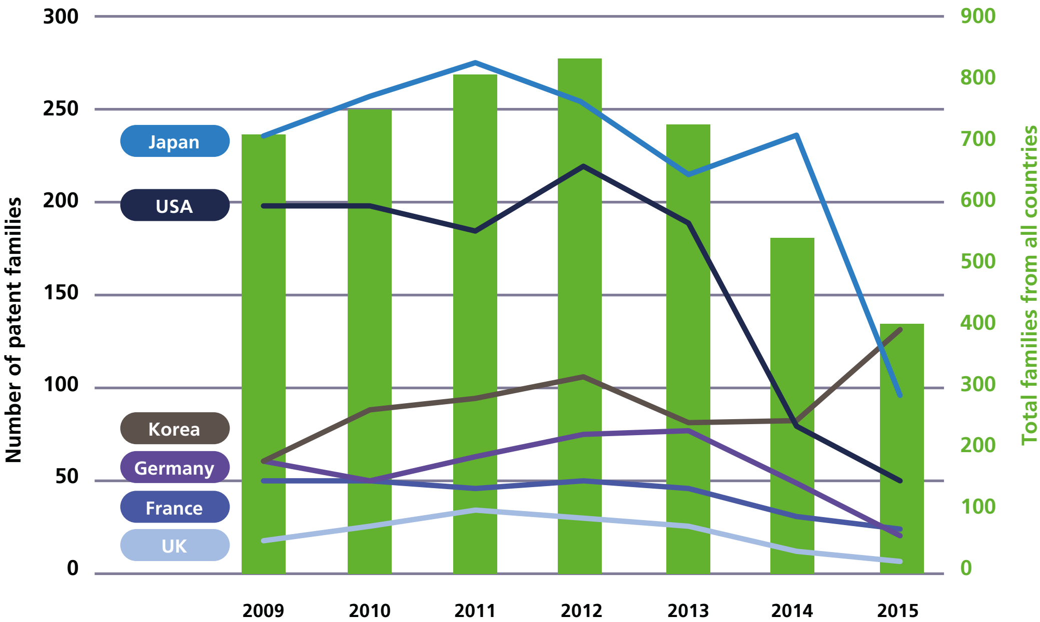


Figure 7. Published patent count from 2009 to 2015 for the top five inventor countries and the UK. *Data source: PatSeer.com. The bars show the total hydrogen and fuel cell patent families from all countries.*

51 We consider only simple patent families of size ≥2, a commonly used criterion for higher quality patents in international comparison studies. See, for example, Haščič et al. (2015) The use of patent statistics for international comparisons and analysis of narrow technological fields.

Patent data provide some insight into patterns of international collaboration of UK companies. UK patents (defined here as those invented in the UK) have co-inventors from 26 countries. The USA is the most common collaborator, followed by France and Germany. Co-creation of IP with leading Asian countries is low.

More populous countries, with bigger economies, are likely to dominate any given area of science and technology in absolute terms. Relative measures provide a useful insight into the extent to which countries are successfully specialising. One measure of relative technology performance in a given area is "revealed technology advantage" (RTA). This measures the difference between a given country's share of H2FC patenting, and its share of patents in all energy technologies. Countries that patent disproportionately in H2FC relative to their average patent share can be thought of as more specialised in H2FC, and performing relatively better in this area. When this is the case, RTA > 1.

Of countries leading H2FC innovation, several have shown specialisation in H2FC technologies (i.e. RTA > 1) during the period 2009–2018 (Figure 8), including the UK. Between 2010 and 2015, most comparator countries reduced H2FC patenting relative to other technologies. The reduction was particularly marked in Japan, the USA and Canada. The main exceptions were Korea and the UK, suggesting a relative increase in the UK developing novel H2FC technologies in recent years.

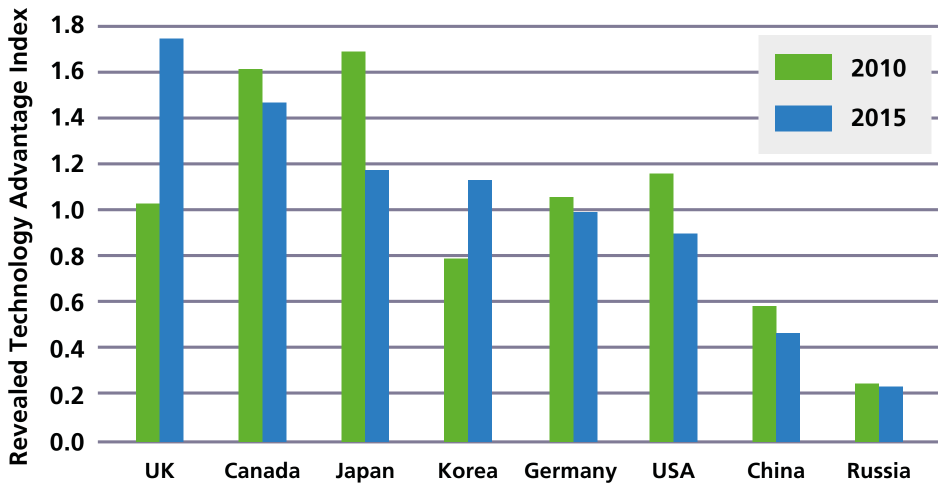


Figure 8. Specialisation index Revealed technological advantage (RTA) of H2FC patents filed internationally in 2010 and 2015. *RTA = 1 when countries patent H2FC technologies at the same intensity as other energy technologies; where RTA > 1 this shows the country is more successful in generating H2FC technologies than other energy technologies. Calculated using higher value patents (family size ≥ 2). Data source: OECD.*

Patent citations are a widely used measure of the quality of inventions. When new patents are filed, they must refer to relevant 'prior art', generating a record of citations.[52] Inventions that are more influential receive more citations, and forward

52 In a new patent, citations of prior patents are termed "backward citations". References to a patent by other patents published in the future are called "forward citations".

citations correlate with patent value.[53] Patents with a UK inventor have received an average of 6.4 forward citations, behind those from the USA and Canada (with 13.5 and 10.7 respectively), but ahead of those from Germany, Japan, Korea, France or Italy (all below 5). Patents with UK-based inventors also tend to be filed in more countries, which is a further suggestion that such patents are high quality.[54] Seeking patent protection in multiple jurisdictions is costly, and reflects the inventor's confidence in the value of the invention.

For most years between 1990 and 2010, the UK had much lower public investments in energy R&D than many other developed economies.[55] As a result, UK companies have not tended to be world leaders in the development of new energy technologies, with the exception of marine energy. However, patent data suggests that the UK performs relatively better in H2FC than it does in other areas of low-carbon energy (Figure 9). This suggests an important message: as markets for low-carbon technologies grow globally, it makes sense for the UK to specialise in areas in which it can hope to achieve some comparative advantage. H2FC technologies appear to offer an arena in which the UK has relatively good performance.

> **Patent data suggests that the UK performs relatively better in hydrogen and fuel cells than it does in other areas of low-carbon energy on average.**

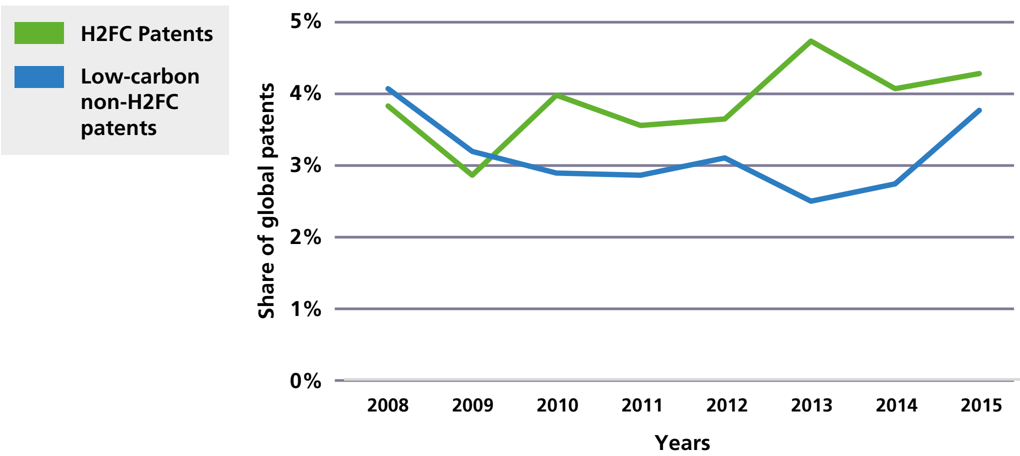


Figure 9. UK patent shares in H2FC vs. other low-carbon energy technologies.
Data source: OECD. Calculated using higher value patents (patent families of size ≥2).

3.4.2 The science base for H2FC technologies in universities

Academic institutions play an important role in technology innovation systems by providing a supply of skilled graduates and researchers, and by conducting research that can underpin technological development. The H2FC Supergen Hub has identified more than 80 academics researching hydrogen and fuel cells at 24 UK

53 Harhoff D. (1999) Citation frequency and the value of patented inventions.
54 Harhoff D. (2003) Citations, family size, opposition and the value of patent rights.
55 Based on data reported by countries to the IEA.

universities.[56] The UK has expertise in each broad H2FC research area in at least 10 universities, as shown in Table 2. The businesses that responded to our survey perceived the UK's strong science base in universities as a particular strength of the UK's H2FC sector.

> **Businesses perceive the UK's strong science base in universities as a particular strength of the UK's hydrogen and fuel cell sector.**

This picture of strength is reflected in patterns of global research output. Globally, scientific research (measured by published journal articles) on hydrogen and fuel cells has grown substantially over the last 20 years. As Figure 10 shows, worldwide H2FC papers have increased by a factor of 10 in the past 20 years, and the UK has kept pace with this increased activity.

Research area	Number of universities with research programmes
High temperature fuel cells	10
Low temperature fuel cells	12
Hydrogen production	11
Hydrogen storage and safety	10
System design, modelling and socioeconomic analysis	10

Table 2. UK academic expertise in H2FC research areas.
Source: EPSRC H2FC Supergen Hub data.

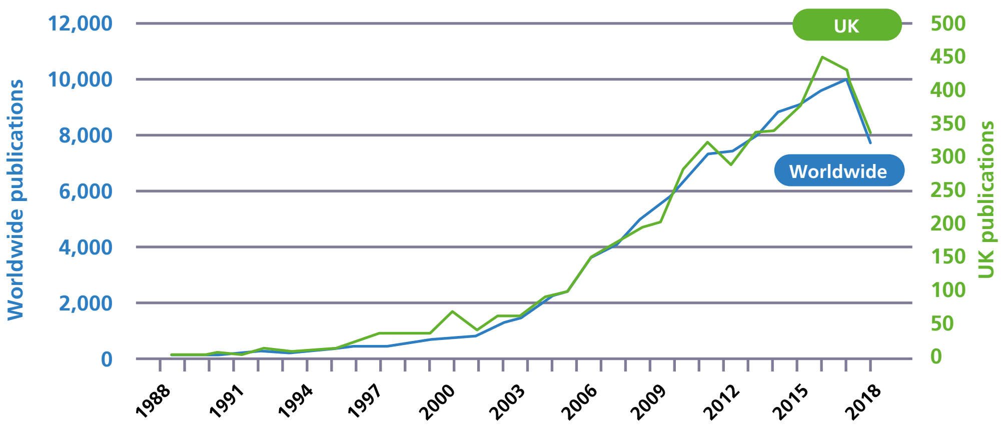


Figure 10. Comparison of UK and global academic publications on hydrogen and fuel cells.
Data source: WebofKnowledge.com.

However, overall numbers of published papers are a crude measure, as they tell us little about the quality or influence of the research activity. Citation data is potentially more useful, as high-quality and novel research should receive more citations.

56 EPSRC H2FC Supergen Hub (2019) UK H2FC Capability Document.

We use two measures here:

- **Average citations per paper.** This provides an indicator of the quality of scientific work conducted in a country and represent the average number of times that a record has been cited for the years in the dataset.
- **The h-index.** This provides a combined measure of both the quality and volume of publications. The h-index denotes the number of papers from a country that have been cited by others at least that same number of times (thus an h-index of 25 means that 25 papers have received 25 or more citations).

These metrics are graphed for key countries in Figure 11, for H2FC publications in the years 2008 and 2013. Items published in 2008 have higher citations as they have been in print much longer. The UK produces world-leading research: the high 'average citations' figures in 2008 demonstrate that British efforts in this area are at the cutting edge. But it is also clear from the h-index that China and the USA, which tend to have larger R&D investments, have a substantially greater output of well-cited research.

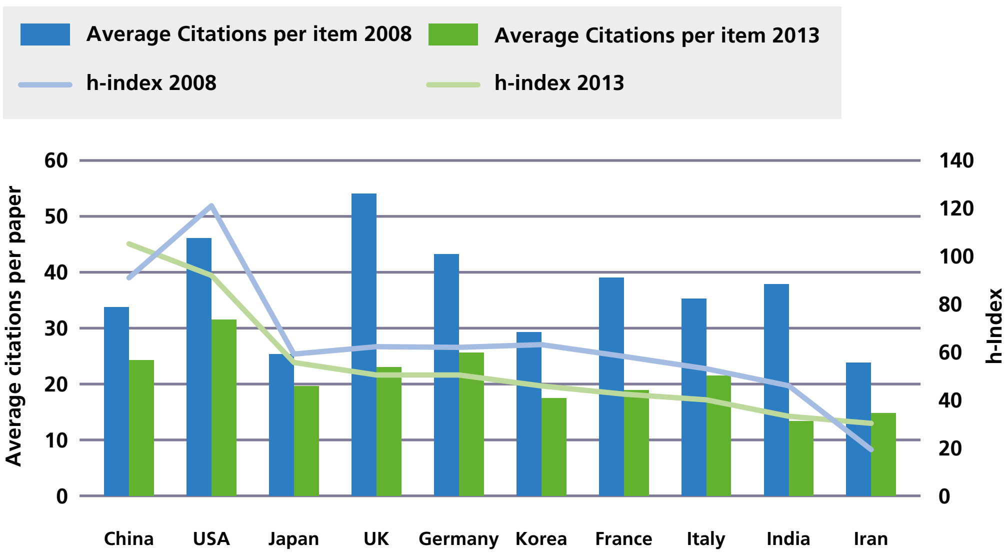


Figure 11. Quality of publications by author's country for the years 2008 and 2013. If, for example, a paper has authors from the UK and the USA, then it will be included in both UK and USA bars on this graph. *Data source: WebofKnowledge.com.*

Analysis of patterns of co-authorship also provide some insights into the depth and nature of the relationships between UK universities and companies. Japan, for example, shows a high degree of co-authorship with industry: 12% of scientific papers have a business-affiliated co-author. In contrast, the UK figure is 4%, suggesting a weaker degree of collaboration. It is also notable, though not surprising, that German, Japanese and American academics often publish with authors affiliated with automotive majors: Daimler, Toyota, Honda, GM and Ford, for example. In contrast, prominent business affiliations of H2FC papers in the UK are those involved in fuel cell components or stacks, such as Johnson Matthey, Ceres Power and Intelligent Energy.

Similarly, patterns of international co-authorship provide some indication of the degree to which UK scientists are well networked internationally. A large proportion (around 60%) of UK scientific publications include authors with international affiliations, much higher than those in the USA (40%) or Japan, China, and Korea (all around 30%). This suggests that the UK science base is very active in global collaboration networks, suggesting a strong capacity to access and absorb the leading-edge research globally, rather than relying on home-grown knowledge alone. However, it also means that UK expertise is shared with competitor countries, in which their closer industrial collaborations might increase their competitiveness compared to UK partners.

> **Around 60% of UK scientific publications include authors with international affiliations.**

The results of our survey indicate that this international outlook is shared by UK-based H2FC companies. More than 60% of respondents had conducted joint R&D projects with a partner in Europe, and 33% with a partner in North America.

3.5 RESOURCES: PUBLIC AND PRIVATE INVESTMENT IN H2FC IN THE UK

The high research and development (R&D) intensities of ITM Power and Ceres Power that were discussed in Section 3.2 are typical of companies working on emerging technologies such as electrolysers and fuel cells. Of the companies responding to the survey that are mostly or exclusively involved in H2FC activities, all except those providing consulting services reported R&D expenditure exceeding 20% of revenue. Information on R&D investments provides a picture of the innovation-related activity in the UK, by shedding light on the geographic breakdown of activity, trends over time, and the share of activity among those conducting R&D (e.g. universities or companies) and those providing it (UK or EU funders).

Data on private-sector investment in R&D specific to H2FC is not systematically collected and no robust estimates are available. Some direct public investment and support data are available and are discussed in the following section. These exclude indirect public support for H2FC in the form of R&D tax credits, which the survey showed were used by almost all R&D-active companies. For the UK as a whole, R&D tax incentives are a similar magnitude to direct grants for R&D to businesses.[57]

57 OECD (2017) Review of national R&D tax incentives and estimates of R&D tax subsidy rates 2016. Deliverable 3.1 of the TAXINNO project, OECD, Paris.

3.5.1 UK public sector funding

Information about public funding for research and innovation in the UK is provided through a number of different institutions and channels, and not all clearly identify the H2FC component:

- **R&D tax credits.**
- **UK Government:** for innovation programmes in hydrogen for heating and hydrogen production based on adapting existing technologies.
- **Other UK government and local authorities:** for hydrogen refuelling stations and fuel cell buses.
- **Innovate UK:** as part of an H2FC programme that supports the development of novel products.
- **European Union:** for basic science and for nascent deployment programmes to create new markets.
- **Engineering and Physical Sciences Research Council (EPSRC):** for basic science.

The overall pattern of spending over time can be drawn from data collected by the International Energy Agency (IEA). This data makes clear that the UK has not made substantial public investments in energy-related R&D in recent decades,[58] for either H2FC or other energy technologies more generally. More recently, public R&D expenditure on energy has grown, and this has included funding to H2FC. As a result of these trends, UK public investments in H2FC have been lower than in many comparator countries – not because the UK has made choices to de-prioritise H2FC technologies, but rather as a result of very low spending on energy R&D in general.[59]

A significant share of public support for H2FC-related research and innovation is dedicated to fundamental science and R&D in universities through UK Research and Innovation (UKRI), and specifically the Engineering and Physical Sciences Research Council (EPSRC). The EPSRC invested £17m in hydrogen and fuel cell research linked to the H2FC Supergen Hub in the period 2013–2019.[60] It currently has a portfolio with £11m invested in H2FC research and £11m invested in training.[61] Since 2017, a Centre for Doctoral Training in Sustainable Hydrogen has been funded, together with £4m of projects lying at least partly in the H2FC area. However, despite the increased interest in hydrogen and fuel cells, research funding has been reducing in recent years, and there are now few hydrogen projects and almost no active fuel cell projects.

58 Winskel M. (2014) Remaking the UK's energy technology innovation system: From the margins to the mainstream.

59 IEA (2019) IEA Energy RD&D Statistics, 2019 Edition.

60 Figures calculated by the EPSRC H2FC Supergen Hub.

61 EPSRC research portfolio data taken from the EPSRC website. Where investments cross research areas, the EPSRC splits the funding proportionately between those areas. Training funding was for two Centres for Doctoral Training, on fuel cells in 2014 and hydrogen in 2019.

> **Academic research funding has been reducing in recent years, and there are now few hydrogen projects and almost no active fuel cell projects.**

Another part of UKRI, Innovate UK, is a major source of grants for R&D and innovation within businesses. Since 2014, Innovate UK has funded around 66 H2FC projects, with a total value of £33m. Projects are led by companies, but sometimes include university partners.

Further support has also been made available through larger programmes organised by the UK Government and Ofgem, for example:

- £33m to develop technologies to supply bulk hydrogen in the BEIS Low Carbon Hydrogen Supply Competition. Funding to develop five demonstration projects was announced in February 2020.
- £18m to develop four industrial decarbonisation demonstration projects that are all considering hydrogen to some extent.
- £25m to examine the potential for using hydrogen as an alternative to natural gas for heating buildings and industry in the BEIS Hy4Heat programme.
- £23m to accelerate take-up of hydrogen vehicles and roll out refuelling infrastructure in the Hydrogen Transport Programme, launched in August 2017.
- £9m to provide critical evidence to support the viability of converting the UK gas distribution networks to 100% hydrogen in the H21 NIC project, funded by Ofgem in November 2017.

In August 2019, the UK Government announced its intention to launch a £100m Low Carbon Hydrogen Production Fund in 2021.[62] One goal of the scheme is to encourage private sector investment in low-carbon hydrogen to support scale-up and market development.

3.5.2 European funding: Horizon 2020 (2014–2020)

The European Union, through framework programmes and Horizon 2020, has been a major funder of the UK's H2FC research and innovation activities. Since 2014, the EU has spent more than €500m on H2FC R&D and demonstration projects, from which 53 UK-based organisations have received a total of €77m (14% of the total). The UK's success in winning Horizon 2020 money to support H2FC is roughly in line with the UK's relative size within the EU (the UK accounts for 15% of EU GDP).

Horizon 2020 funding supports both the public and private sectors. For H2FC, €58m has been granted to UK industry, €13m to academia, and €5m to local governments for demonstration projects.

62 BEIS (2019) Hydrogen-powered distillery to produce sustainable gin.

UK companies have tended to take on a leadership role in a relatively large share of multi-country projects. UK partners have participated in half of European-funded H2FC collaborative projects, which is similar to France and Italy but behind Germany (who are involved in 75%).

Other European sources of funding have also supported UK hydrogen energy developments. For example, the European Regional Development Fund (ERDF) has supported the £15m Flexis project in Wales, and a range of projects through the Low Carbon Infrastructure Transition Programme in Scotland.

3.5.3 Private sector investment

H2FC start-ups use the same sources of investment funding as companies in other sectors.

As markets for H2FC technologies have started to emerge in several countries, large enterprises are increasingly expanding their H2FC operations. Weichai, Bosch, Cummins, Linde and Doosan have invested more than $1bn over the last 18 months, with Ceres Power alone receiving £150m of foreign direct investment.

3.6 PROSPECTS AND CHALLENGES: THE BUSINESS ENVIRONMENT FOR H2FC

The companies with H2FC interests that responded to our survey were optimistic about the future. They saw strong growth potential for the sector as a whole, both in the UK and internationally. They were optimistic about their own competitive positions, and the prospects for their own companies.

3.6.1 UK-based companies see strengths but also threats for the UK's emerging H2FC industry

Respondents highlighted a number of strengths of the UK H2FC industry, relative to other world regions (North America, Europe, and East Asia). Most prominent was the belief that the UK's research and science base for H2FC is a relative strength. The UK is seen as having high quality universities that produce world-leading research related to H2FC technologies. This is at odds with the finding in Section 3.4.2 of low co-authorship between companies and universities in the UK, compared to leading countries. The reason for this discrepancy is not known. Respondents also thought that the UK has a good business environment for innovation and business development.

Respondents highlighted areas in which the UK is weak relative to comparator countries. The most prominent concerns related to access to finance, policy support for UK market development, and the availability of employees with the required skills. Other European countries and East Asia are seen as having stronger policy support for H2FC, while finance is considered easier to access in North America and East Asia. Europe, North America and East Asia are all considered to have a better stock of labour with the appropriate skills.

Several respondents expressed the concern that, despite positive overall prospects for the sector, the UK was losing out to other regions. Near-term markets are seen as most likely to grow outside the UK, creating a challenge for UK-based companies. This concern is not reduced by the international orientation of the companies surveyed (two thirds of the UK-owned H2FC companies in our survey sell outside the UK, especially to Europe, with around half selling to North America or to Asia).

> **Diffculties accessing finance, weak UK markets, and a shortage of skilled employees are the most important issues for companies in this sector.**

In summary, the survey revealed a sense that the business environment for H2FC risks failing to incubate a globally-competitive H2FC sector, despite the presence of a world-leading science base in the technologies.

3.6.2 Building capabilities: R&D, networking and demonstration activities

Most of the responding companies that have a significant focus on H2FC (defined here as more than 20% of their business) are small or micro, and almost all are R&D intensive: the companies report significant R&D activity, and they cite R&D as a key mechanism for development. R&D activities are reported to be highly collaborative, both with other businesses (across the world), and with universities. Almost all of those reporting significant R&D activity in the UK have partnered with universities.

The surveyed companies are active users of the government's array of R&D support mechanisms: almost all of them have made use of R&D tax credits, and many others have been recipients of grants from the EU, Innovate UK, or the Office for Low Emission Vehicles (OLEV). The companies are typical of respondents to the UK Government's innovation survey in this regard.[63] While these are clearly important forms of support, respondents also noted that the administrative requirements of such grants were a major challenge in securing support, particularly for small and micro businesses.

Companies in the survey identified participation in demonstration projects – along with R&D and networking with customers and suppliers – as a key mechanism for building knowledge and the capacity to innovate.

63 BEIS (2020) UK Innovation Survey 2019.

CHAPTER 4 - OPPORTUNITIES AND BENEFITS FOR THE UK

INTRODUCTION

The previous section demonstrated the varied strengths of the UK in hydrogen and fuel cell innovation. A key challenge for the UK is to convert these strengths into prosperous economic activities. The availability of a market for hydrogen and fuel cell technologies is a prerequisite for successful innovation, which would otherwise stall in the absence of investment and technology deployment. All countries with nascent hydrogen industries provide public funding support in some form to support the creation of a market. It is important to justify this support. Four perspectives are examined here:

1. Potential benefits to society that could be realised through investing now.
2. Potential longer-term economic benefits of investing.
3. Clean growth opportunities for UK industry.
4. International competition.

4.1 POTENTIAL SHORT-TERM BENEFITS OF HYDROGEN AND FUEL CELL TECHNOLOGIES

A range of niche markets for hydrogen and fuel cells was identified in Section 2.2. While some of these are driven by the technologies becoming the most economic option (e.g. emergency power supplies; forklift trucks), the development of most hydrogen markets globally is being driven by public sector support. This support is necessary because incumbent technologies are cheaper than new technologies. One reason for this price disparity is the need for innovation, which is underpinned by manufacturing and the public using new technologies. Another is the lack of levies on existing technologies to represent environmental externality costs, which cause the environmental benefits of low-polluting technologies such as fuel cells to not be recognised by the market. Those benefits are not often quantified.

Two types of externality costs can be considered. Damage costs quantify the harm caused by a technology polluting the environment. Mitigation costs are the additional costs of using alternative low-pollution technologies instead of existing technologies.

For greenhouse gas emissions, the damage costs are very difficult to assess, as damages occur globally rather than just in the UK, and the scale of the damage and hence the costs depends on the cumulative emissions over decades. Mitigation cost is more straightforward to calculate. The EU Emissions Trading Scheme has produced a price of carbon in the range €5–30/tCO_{2e} over the last few years. If we apply a €30/tCO_{2e} to an average diesel car meeting Euro 6 standards, then the carbon cost would be around £70/year. For a London black cab meeting the same standards, the cost would be around £200/year. These costs are not large enough to justify moving to an alternative technology, which is why decarbonisation efforts to date have concentrated in other sectors.

On the other hand, emissions of air pollutants such as NO_x and particulate matter have immediate and local air quality impacts that harm health, particularly in urban areas. The damage costs from these emissions, for the same average diesel car and black cab meeting Euro 6 standards, can be estimated using data from DEFRA[64] and the TRUE initiative.[65] The costs are around £100/year for an average diesel car, but £2,000/year for an average black cab operating in inner London.[66] Such large environmental externalities could be avoided by using fuel cell vehicles, and the high-mileage nature of taxis is particularly suited to technologies with higher capital costs. Plug-in hybrid black cabs have been developed that use a range extender to recharge the batteries when the taxi is driving longer ranges. At the moment, the range extender is a diesel engine, emitting air pollutants, but there is no reason why a fuel cell range extender could not be used instead. It would be useful to carry out these damage cost calculations on a range of vehicle types to better identify niches that are particularly suited for early adoption of low-carbon technologies.

Urban fuel cell buses have already been trialled in London and Aberdeen, and Wrightbus recently developed a double-decker version. Refuse collection trucks similarly produce substantial emissions in urban areas and are another potential early adopter of H2FC technologies to improve air quality. As they operate from a single depot, for refuelling, and are part of a public fleet, they are particularly suitable for public investment in new infrastructure and vehicles. While battery refuse trucks with fuel cell range extenders have been trialled, the first fuel cell-powered refuse trucks are only now being developed by the REVIVE project.[67] Hydrogen is particularly well suited to heavier vehicles operating daily duty cycles. The UK could benefit from a focus on developing buses, trucks, vans, and even boats, where there is already some industrial strength.[68]

Finally, from a clean growth perspective, the UK is unlikely to achieve substantial industrial strength in H2FC unless it invests in the technologies in the short term in order to build a domestic knowledge base and industrial strength.

FOSTERING UK MARKETS

Recommendation

Use public procurement and subsidies to create a market for fleets of vehicles.

FOSTERING UK MARKETS

Recommendation

Build a basic national refuelling station network for public and private use to enable the use of fuel cell vehicles across the UK.

64 DEFRA (2019) Air quality damage cost guidance.

65 TRUE (2018) NO_x and particulate emissions from London's taxis.

66 One reason for these high costs is that real-world NO_x emissions from diesel cars and diesel taxis exceed the Euro 6 laboratory emission limits by a factor of 2–4.

67 The EU REVIVE project is integrating fuel cell powertrains into 15 vehicles and testing them at 8 locations across Europe.

68 E4tech and Element Energy (2016) Hydrogen and Fuel Cells: Opportunities for Growth.

This means creating sufficient hydrogen infrastructure to refuel vehicles, and sufficient demand for hydrogen to underpin investments by industry.

4.2 POTENTIAL LONGER-TERM ECONOMIC BENEFITS OF INVESTING IN A HYDROGEN ECONOMY

A range of studies have identified a strong future role for hydrogen in a low-carbon energy system. Section 2 identified opportunities to decarbonise heating, transport, and industry. Several of these opportunities are unlikely to be realised at a large scale until the 2030s or 2040s.

4.2.1 Potential economic impacts of hydrogen and fuel cell investments

The E4tech study of European H2FC value chains examines a scenario in which 2.6 million fuel cell cars and a range of heavier vehicles are operating in Europe in 2030, together with some stationary CHP fuel cells. They estimate the value of annual EU H2FC manufacturing in the range €8bn–€10bn, depending on how much of the market EU companies are able to capture, and €1bn operating and maintenance income.[69] Around a third of this value would be realised as profit, and this would be split between companies across the value chain. This analysis does not include the value of supporting business functions such as logistics, finance, marketing, and sales, nor the provision of hydrogen to fuel the vehicles. A similar analysis of value chains has not been carried out specifically for the UK, but would be valuable.

An H2FC Supergen Hub study has examined the implications of replacing petrol and diesel with hydrogen for transport purposes using a whole-economy, input-output model.[70] This approach analyses the wider indirect economic benefits of moving to a new technology. For each £1 spent on petroleum, total economic activity of almost £1.50 occurs due to indirect value from industries in the supply chain, and induced value from people employed in those industries that spend money. This is unusually low because the sector is import-dependent. Hydrogen, in contrast, could be produced using electrolysis and/or exploiting current gas supply networks, so there is potential for developing strong domestic supply chains, which also generate value indirectly in the service sector. Assuming a predominantly domestic supply chain, the study estimates higher economic activity of around £2.50 would occur for each £1 spent on hydrogen. Such benefits are deeply uncertain and are contingent on successful implementation of policy, and it would be valuable to carry out further research to understand the importance of the study assumptions and to widen the analysis to other H2FC areas, perhaps using a computable general equilibrium (CGE) model.

> **Hydrogen is expected to have substantially larger indirect benefits for the UK economy than petrol and diesel.**

69 E4tech et al. (2019) Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies.

70 Turner K. (2018) Framing policy on low emissions vehicles in terms of economic gains: Might the most straightforward gain be delivered by supply chain activity to support refuelling?; Smith et al. (2017) The Economic Impact of Hydrogen and Fuel Cells in the UK.

4.2.2 Potential employment impacts of hydrogen and fuel cell investments

The E4tech study estimates that 80,000–110,000 jobs could be supported by H2FC industries in Europe by 2030, in either direct manufacturing, maintenance, or indirect manufacturing (e.g. jobs supplying the non-H2FC parts of the application, such as the car chassis). Further jobs would be created in supporting business functions.

The H2FC Supergen Hub study calculates that vehicle manufacturing has 3.2 direct jobs and 10.4 induced and indirect jobs for every £1m of final demand spending. This is important for the UK because automotive manufacturing, and trade, are substantial. For example, in 2018, the UK exported 80% of all manufactured vehicles, with a value of £44bn, while importing 90% of vehicles sold in the UK, with a value of £57bn.[71] If the UK were to greatly reduce exports while continuing to import most of its vehicles, then this would have a substantial impact on UK employment. On the other hand, even if the UK were to reduce vehicle manufacturing, the impact could be greatly reduced if it were to capture greater parts of the complex supply chains of fuel cell vehicles.

> **80% of cars manufactured in the UK are exported.**

4.3 CLEAN GROWTH OPPORTUNITIES

Many H2FC technologies are on the cusp of commercialisation. The various components have been developed through basic science over a period of decades, and the focus is now on continuing incremental improvements, and system integration into commercial products. Many companies are developing H2FC products in the UK, whether by introducing new technologies or converting existing ones to use hydrogen. Since insufficient public innovation funding will be available to support all activities, it is necessary to identify the strongest opportunities. UK strengths can be categorised into three groups:

- **Strength in existing technologies.** For example, the UK has a large engine and car manufacturing industry, which can be expected to increasingly shift towards producing low-carbon vehicles. Many of the skills in the existing workforce, and factories, could be repurposed for fuel cell vehicles. A skilled engineering base to develop and manufacture technologies in the UK, to sell into the European market, is a key attraction for foreign investors.

- **Strength in novel H2FC technologies.** The UK has industrial expertise in fuel cell and electrolyser design and manufacturing, and also in materials and in other parts of the supply chain. These areas are primarily, but not exclusively, focused on electrochemical technologies. For hydrogen, the UK has design and systems integration expertise.

71 SMMT (2019) 2019 UK automotive trade report.

- **Strength in related low-carbon technologies.** For example, the UK has invested in battery mobility technologies through the Faraday Challenge. Electrochemical technologies such as batteries and fuel cells have similar engineering challenges, and batteries are an integral part of fuel cell vehicles, so investment in both offers greater potential rewards than investing in either individually. It would be useful to assess the potential to leverage insights through technology spill-overs to support fuel cell development.

Supply chains for end-use technologies are complex. For example, a fuel cell vehicle has a number of subsystems including a fuel cell stack and a hydrogen tank. The stack contains sub-components such as membranes and gas diffusion layers, and these contain specialised materials such as catalysts. It is very unlikely that the UK would capture the entire value chain, but it is well placed to capitalise on important parts of the supply chain. Johnson Matthey is already a leading manufacturer of membrane electrode assemblies. The E4tech study showed that added value occurs throughout the value chain and can be particularly high at the component and sub-component levels.[72] There is arguably a need for specialisation, which could focus on likely uses of these technologies in the UK, in areas where the UK has a competitive advantage over other countries, or both.

In addition to some of the specialist technologies that are described above, the UK has traditionally had expertise in system integration, consultancy, and professional services. These comparative advantages have value globally and could also complement UK industrial development.

4.3.1 Automotive sector

The principal goal of investing in fuel cell vehicles would be to defend the existing UK automotive industries. In 2017, the UK automotive sector turnover was £85bn, with employment of 856,000, and substantial exports.

The UK has chosen to support automotive battery development through the Faraday Challenge (£246m), and electric motors through the Driving the Electric Revolution Challenge (£80m). While both of these investments are targeted at battery electric vehicles, they are also components in fuel cell vehicles.

One option to try to maintain existing industrial strengths would be through investing in related new technologies – for example, by manufacturing electric motors and fuel cells in regions with factories which are producing internal combustion engines.

> **By supporting fuel cell as well as battery electric cars, the UK can ensure that it is well placed to support its automotive sector if either powertrain becomes dominant in the future.**

East Asian manufacturers (Hyundai, Honda, and Toyota) are leading the development

72 E4tech et al. (2019) Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies.

of H2FC cars, and these operate primarily in Japan, Korea, and California, where networks of hydrogen refuelling stations have been constructed. Assembly line manufacturing has only recently commenced and around 11,000 cars were on the road worldwide by 2019. European and USA manufacturers have tended to focus on battery electric vehicles, for which the batteries comprise a substantial part of the total added value. Fuel cell vehicles, in contrast, are more similar from a value perspective to internal combustion engine vehicles. One notable UK car company is Riversimple, who have designed a novel and highly efficient fuel cell car rather than fitting fuel cells to existing designs, and aim to launch a commercial model in 2022.

4.3.2 Hydrogen for heating

In the short-term, hydrogen could be injected into the gas networks in small volumes to partially decarbonise the gas supply. This would reduce CO_2 emissions and generate demand for hydrogen. The HyDeploy project is testing the concept in Keele, and plans further demonstrations in villages in North East and North West England.

The UK is leading global efforts to understand whether hydrogen could power boilers to decarbonise heating. These efforts are a consequence of the extensive UK natural gas network and its perceived suitability for delivering hydrogen, and the popularity of gas boilers with the UK population. BEIS and Ofgem have funded substantial programmes to examine the technical feasibility and challenges, and the economic viability. The BEIS Hy4Heat programme is developing a range of hydrogen-powered home appliances.

Micro-CHP fuel cells could be used as an alternative to boilers to provide in-house heat and electricity generation. Since these fuel cells would operate during the coldest periods, they would help to offset high electricity demands if heat pumps were widely adopted. Fuel cells would also have lower NO_x emissions than boilers.[73] The leading investor in fuel cell CHP is Japan, who have deployed more than 300,000 units powered by natural gas, and with the potential to be powered by hydrogen in the future. Ceres Power have also developed a novel lower-cost fuel cell stack that has the potential to compete successfully with Japanese and Korean CHP technologies (Section 3.2.2).

4.3.3 Hydrogen in industry

The UK Government has identified six large industrial clusters in the UK with annual greenhouse gas emissions in the range 2.6–12.4 $MtCO_2$. It aims to deploy low-carbon infrastructure to decarbonise at least one of these clusters by 2030. There is an opportunity to create a large market for hydrogen in a cluster that would enable scale-up of hydrogen production.

> **There is an opportunity to create a large market for hydrogen in an existing industrial cluster that would enable scale-up and cost reductions for hydrogen production.**

73 Catalytic boilers have been proposed to reduce or even eliminate NO_x emissions from hydrogen boilers.

4.3.4 Hydrogen production and delivery

Section 2.1 showed that demand for low-carbon hydrogen is likely to ramp up in the future, both in the UK and abroad, but that the future UK demand is uncertain. The Royal Society examined four groups of hydrogen production technologies and identified steam methane reforming and electrolysis as the most likely technologies to produce low-carbon hydrogen at volume in the near to mid term.[74]

The principal challenge for low-carbon steam methane reforming is to maximise the CO_2 capture rate, particularly with the UK moving to a net zero target. Johnson Matthey has developed a conceptual high-efficiency plant, with a high capture rate, and BEIS have funded research to further develop and evaluate the design.

Electrolysers have been used for many decades, but deployment is low and global growth is much lower than for fuel cells.[75] There are three broad designs – alkaline, proton-exchange membrane, and solid oxide – and it is not clear which will be most successful in the future. There has been much focus on PEM electrolysers in recent years as their ability to change power output very quickly makes them ideal for power-to-gas applications using excess wind and solar generation. ITM Power is a leading manufacturer of PEM electrolysers (Section 3.2.1). Alkaline electrolysers have been used commercially since the 1920s but are still being actively developed, including by the UK-based AFC Energy. UK companies do not have a leading role in solid oxide electrolysers, but the potential for CERES Power's fuel cell stack to be adapted to produce a novel electrolyser design is being examined.

Producing low-carbon hydrogen at a sufficiently low cost has been identified as a key challenge for the UK (Section 2.3.1). BEIS have funded five demonstration projects, and are also examining possible business models and subsidy needs. Separately, a report for the UK Government has identified the supply of low-carbon, hydrogen-based fuel for international shipping as a potential future UK growth area.[76]

A reliable hydrogen supply is required if fuel cell vehicles are to be deployed in the UK. There is a burgeoning global market for hydrogen refuelling stations in which several companies, for example ITM Power and Shell, are involved. Their refuelling stations currently have a single hydrogen pump with an electrolyser capable of producing 80 kg hydrogen each day, which is enough for about 16 full car tanks. In comparison, a busy diesel pump might service perhaps 100 cars each day, and UK refuelling stations have around seven pumps on average.

4.3.5 Components and materials

Companies across Europe specialise in components and materials for fuel cells. In this regard, the supply chains for H2FC technologies are not dissimilar to the Europe-wide supply chains that already exist in the automotive sector. Many existing and emerging UK companies (or international companies with a UK presence) have strong

74 Royal Society (2018) Options for producing low-carbon hydrogen at scale.
75 E4tech (2018) The Fuel Cell Industry Review 2018.
76 E4tech et al. (2019) Reducing the maritime sector's contribution to climate change and air pollution.

capabilities in a range of fuel cell and hydrogen component supply chains. These range from large established companies (e.g. Johnson Matthey) to smaller emerging companies (e.g. Amalyst; Promethean Particles Ltd). This is one area in which the UK can take advantage of domestic research strengths in academia to augment the links between universities and companies.

> **Many existing and emerging UK companies have strong capabilities in a range of fuel cell and hydrogen component supply chains.**

Much of the added value of hydrogen will be in the form of infrastructure.[77] Refuelling stations in particular offer opportunities for innovations in electrolysers, compressors, storage, flow meters, and ancillary equipment. Such technology integration opportunities support a range of companies and should not be overlooked.

4.4 INTERNATIONAL COMPETITION FOR THE UK H2FC INDUSTRY

While replacing natural gas with hydrogen for heating is potentially an economic and technically-viable option for the UK, it might not be viable in many other countries.[78] If this is the case, it is unlikely to be realised unless the UK invests in boiler designs and hydrogen technologies for the UK gas networks. On the other hand, Japan has invested heavily in fuel cell micro-CHP and could target the UK heating market if the UK Government decides to convert the gas networks to deliver hydrogen.

Asian companies are leading the development of fuel cell cars as a future export industry. In contrast, heavier fuel cell vehicles (e.g. buses and HGVs) are being developed by companies around the world and there is no clear leader.

The UK could potentially produce hydrogen from renewables more cheaply than its European neighbours. It has substantial renewable generation capacity, particularly through offshore wind, that could supply electrolysers if a market for low-carbon hydrogen develops. If fossil fuels were instead used to produce hydrogen, then the UK has substantial saline aquifers and offshore oil and gas fields that could be used to store CO_2. These offer the prospect of the UK being at least self-sufficient, and potentially an exporter, of hydrogen, though such scenarios are highly uncertain. It would be important to assess the relative competitiveness of the UK compared to other European countries, to understand whether an export strategy might be viable.

77 E4tech et al. (2019) Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies.
78 Dodds P.E & Demoullin S. (2013) Conversion of the UK gas system to transport hydrogen.

The IEA has recommended the establishment of international trade routes for hydrogen.[79] There is growing interest in the international trade of hydrogen or hydrogen-based energy carriers, such as ammonia, from areas with potentially very cheap renewable generation such as Chile and Australia. This could undermine UK production for both domestic and export markets. A preliminary analysis by the CCC concluded that the cost of imported hydrogen from Chile/Australia would be in the same range as the cost of producing hydrogen domestically. It would therefore be important to also assess potential competition from international trade.

A STRATEGIC VISION

Recommendation

Study whether the UK is likely to be able to build a competitive hydrogen production industry, and whether there is a potential export industry to European neighbours.

Many years of innovation can be required for a technology to reach commercial competitiveness. If the UK were to delay a transition to H2FC and then to deploy H2FC technologies very quickly, without having successful innovation programmes, then it would likely rely on a greater proportion of goods developed overseas and would capture less of the overall value. When studying the potential economic benefits of fostering H2FC supply chains in the UK, it would be useful to also measure a counterfactual scenario in which substantial UK demand for hydrogen would be primarily met through imported technologies as a result of the UK H2FC innovation not being sufficiently supported going forwards.

79 IEA (2019) The Future of Hydrogen: Seizing today's opportunities.

CHAPTER 5 - ACTIONS TO ENCOURAGE HYDROGEN AND FUEL CELL INNOVATION

INTRODUCTION

In order to identify useful actions, three broad insights need to be borne in mind from the previous sections.

First, although hydrogen and fuel cells are closely related from a system perspective, their current state and future needs are different. A range of niche markets for both mobile and stationary fuel cells have developed outside the UK in recent years. The largest use is currently for CHP in Asia, but commercial fuel cell vehicles are now entering the market. In contrast, although low-carbon hydrogen is expected to have an important role in industry, heavy-duty transport and other areas, there are not yet any substantive markets anywhere in the world.

Second, there are many diverse and highly uncertain application areas for hydrogen and fuel cell technologies. A useful first step is to treat hydrogen and electrochemical technologies (fuel cells and electrolysers) separately. The UK already has an export-focused electrochemical sector, and has an opportunity to create a competitive hydrogen sector.

Third, there will always be some misalignment between UK H2FC growth opportunities, optimal domestic hydrogen end-uses, and the industrial and academic comparative advantages of the UK compared to competitors. A strategy needs to consider both UK needs and export opportunities, and identify any differences between these.

5.1 DEVELOPMENT OF MARKETS FOR HYDROGEN AND FUEL CELLS

There is a very well established literature linking market formation and cumulative deployment to induced innovation and cost reduction.[80] Successful early markets drive greater investor interest, generate revenues for re-investment in innovation, enable learning-by-doing, enable relationships with and learning from users and suppliers, and highlight regulatory barriers that need to be addressed.[81] However, it is also clear that subsidising new energy technology markets can be enormously costly, and that expensive attempts to stimulate market growth and associated innovation sometimes fail to generate a large and sustainable domestic industry (e.g. solar PV in Germany).

5.1.1 Fuel cell markets

In the UK, market demand for fuel cells has been supported primarily through demonstration projects and by including fuel cells within existing subsidy schemes (such as the now-expired micro-CHP feed-in tariff). Overseas markets are larger and most UK companies in this sector are exporters. Several companies have attracted substantial foreign direct investment to the UK. As technologies mature, UK demand could continue to be spurred through public procurement and through other carefully

80 Samadi S. (2018) The experience curve theory and its application in the field of electricity generation technologies – A literature review.

81 Gallagher K.S. (2012) The energy technology innovation system.

targeted subsidies. If the UK Government wants to ensure that the UK stands a good chance of benefiting from the emerging fuel cell markets, it needs to ensure that there is support for domestic experimentation and learning, which is necessary for UK companies and domestic capabilities to develop. Japan, for example, has invested heavily in subsidising domestic micro-CHP fuel cell installations.

Fuel cells, as scalable, mass-produced products, can be expected to follow a classic technology life-cycle, with the establishment of a dominant design being followed by a shift from product-focused to process-focused innovation that drives down costs.[82] In the absence of market demand, it is very difficult to justify investments in assembly lines in particular, and this will be a key barrier for companies. Support for investments in R&D related to manufacturing would complement market support, as they would enable companies to accelerate cost reduction processes.

5.1.2 Hydrogen markets

A low-carbon hydrogen market does not yet exist in the UK, or elsewhere, other than with a series of demonstration projects. The IEA identify hydrogen injection into existing natural gas streams as one approach to create demand,[83] and two tests will soon take place in villages in Northern England. Another approach recommended by the IEA would be to create coastal industrial clusters for oil refining, and for ammonia and methanol production, where there are already large demands for hydrogen that are currently met by high-carbon fossil fuels. The Industrial Strategy Challenge Fund (ISCF) industrial decarbonisation challenge could examine these opportunities.

FOSTERING UK MARKETS

Recommendation

Examine opportunities to use low-carbon hydrogen in oil refining, ammonia and methanol production, steelmaking, and elsewhere, as part of the new ISCF industrial decarbonisation challenge.

One challenge is to prove that hydrogen comes from a sufficiently low-carbon production source and delivery route to meet climate targets. A green hydrogen standard could be defined to certify production plants, and a certificates of origin scheme would enable producers to show that their hydrogen met the standard. Germany and France have produced incompatible standards and the EU has recently defined a Europe-wide standard through the CertifHy project.[84] Since the UK has now left the EU, it is likely to need to produce an independent standard. This would ideally be compatible with European standards to enable the certificates to be traded, as there would

FOSTERING UK MARKETS

Recommendation

Create a green hydrogen standard and certificate of origin scheme for the UK to enable the value of green and blue hydrogen to be recognised by the market.

82 Huenteler J. (2016) Technology life-cycles in the energy sector—Technological characteristics and the role of deployment for innovation.
83 IEA (2019) The Future of Hydrogen: Seizing today's opportunities.
84 Velazquez Abad & Dodds P.E. (2020) Green hydrogen characterisation initiatives: Definitions, standards, guarantees of origin, and challenges.

otherwise be a barrier to the sale of low-carbon hydrogen to EU countries.

Different technologies require quite different types of support. Converting an existing gas boiler or internal combustion engine to use hydrogen is unlikely to be an insurmountable challenge, with only the lack of a market preventing their development in the past. Only small changes to assembly lines would be required, and it is unlikely that the costs of such technologies could be greatly reduced through innovation.

There is already global expertise in hydrogen production and delivery infrastructure for industrial applications. Low-carbon hydrogen production and delivery infrastructure would be quite different if hydrogen were first used only for vehicles, which would require standalone refuelling stations, or industry and heating, which would use gas pipes. In order to minimise the risk of underused or stranded assets, the strategy for developing infrastructure would likely vary greatly according to the speed of the transition. One study using a spatial model suggests a staged approach to hydrogen infrastructure development for the transport sector, with pipeline investments only made when demand becomes substantial.[85] There is a need to identify robust development strategies that would minimise costs while meeting the requirements of a wider range of energy system configurations.

Steadily growing a market could reduce the costs of a transition to H2FC technologies. Both cars and boilers have lifetimes of 12–15 years, so substantial numbers would need to be deployed throughout the 2030s and 2040s to avoid higher costs from the early retirement of high-carbon technologies, and preparatory work would be needed beforehand. Transition costs for gas network conversion might be further reduced by requiring all new boilers to be dual-fuel models that could be quickly and cheaply adapted to use hydrogen (while noting that there is still no agreement on the characteristics of dual-fuel boilers).

5.2 COORDINATING INNOVATION FUNDING AND SUPPORT

The UK has supported academic research projects and H2FC innovation in companies for many years. The focus of innovation funding for H2FC has changed substantially over the last three years. Academic research funding has declined to a low level. Innovation funding from Innovate UK has continued, and has been complemented by new and substantial direct strategic investments from the UK Government to better understand the potential for using hydrogen to decarbonise heating and industry, and to reduce the cost of hydrogen production. While academic involvement in Innovate UK projects continues to be encouraged, the UK Government programmes have relatively little academic involvement. It is important that complementary sources of knowledge, expertise and capabilities are being supported in academia to make the most of opportunities that arise from the development of a hydrogen economy. Universities underpin the innovation system by developing new knowledge and

85 Moreno-Benito M. (2017) Towards a sustainable hydrogen economy: Optimisation-based framework for hydrogen infrastructure development.

ideas, enabling knowledge sharing and diffusion, and training skilled researchers. A key barrier for our survey respondents was the availability of labour with appropriate skills in the UK. But this shortage reflects reduced research funding in recent years, which reduces opportunities to train students, and indicates to potential students that hydrogen and fuel cells is not a UK priority and is not a good career choice. At the moment, just as the government is recognising the importance of hydrogen for the future, the reduction to a low level of research funding is likely to diminish one of the UK's key strengths.

A STRATEGIC VISION

Recommendation

Consider whether to coordinate innovation funding from UKRI and the UK Government, and how it could best be invested between industry and academia.

There will always be some misalignment, and hence tensions, between applied and blue skies academic funding, innovation funding for growth and export opportunities, and funding for national needs. In the absence of a national innovation strategy that minimises such misalignments, the mostly uncoordinated approaches of the UK Government, UKRI, and Horizon 2020 are unlikely to take full advantage of existing and new opportunities.

There has been much support for UK transport technology demonstrations from European funding over the last decade in particular. European research programmes have enabled access to wider international networks and participation in emerging European value chains. The prominent role of European funding in supporting the UK's H2FC innovation raises questions about the post-Brexit arrangements for support for the sector. The first issue is whether the overall funding available for H2FC technologies will reduce. The second is whether UK companies and researchers will still be able to access funding mechanisms that involve international collaboration, which are important for fostering UK participation in emerging H2FC value chains. Maintaining UK access to participation in European funding streams, such as the forthcoming Horizon Europe, is likely to be an important part of post-Brexit innovation policy, and it is certainly important for H2FC companies.

A VIBRANT INNOVATION ECOSYSTEM

Recommendation

Ensure there are mechanisms for UK researchers and companies to continue and build on existing collaborations with European counterparts, and access European markets.

Access to finance was a key issue for H2FC companies that responded to our survey, whether from public grants, private investors, or markets. R&D tax credits and Innovate UK are the most widely used forms of support for R&D. Survey respondents described funding processes and decisions as slow and excessively bureaucratic. The administrative requirements of grants are a major challenge in securing funding, particularly for small and micro companies. Innovate UK already provide training sessions for European funding applications, and UKRI could consider how advice and assistance on proposals might be provided more generally to companies to enable their participation in a range of schemes.

The UK does not have a major industrial conglomerate such as Siemens. Such multinational companies can buy emerging technologies developed by small technology-based companies and have the internal resources, both in terms of funds and manufacturing knowhow, to scale-up production for a growing market. But this is not necessarily a barrier to innovation, because emerging UK companies can often pursue overseas investments and joint ventures instead. For example, ITM Power entered into a joint venture with Linde in 2019 to produce electrolysers with capacities exceeding 10 MW. Similarly, CERES Power has agreed joint ventures with Chinese and German companies to bring its technology to market. Companies that develop technologies that are unique, commercially differentiated, and have barriers to entry for their competitors are likely to attract foreign direct investment.

5.3 CHALLENGES AND OPPORTUNITIES FROM INNOVATION PROGRAMMES OVERSEAS

Japan, Korea, and increasingly China are investing particularly heavily to position themselves at the forefront of H2FC technologies.[86] For example, the Japanese Ene-Farm programme has supported the development of micro-CHP fuel cells by several manufacturers for more than 15 years. After an initial demonstration of 3,000 units to test the technology, an innovation programme was created with high initial subsidies for each deployed unit. Subsidies were reduced over time, as capital costs reduced, until they were no longer needed in 2019. In addition, key technical challenges were addressed through research projects whose insights were shared with all manufacturers. Such a successful innovation programme comes at a cost, however – in this case, the equivalent of around €200m per year.[87] Also, there is a balance to be found between driving learning through scale for technologies that are chosen at the outset, and including scope for diversity so that novel ideas such as the Ceres Power micro-CHP design can emerge. The UK Government has not adopted similar programmes, but has an opportunity to if it thinks this is appropriate.

Innovation programmes overseas might offer opportunities for collaboration. UK companies already work closely with European partners through EU funding programmes, and perhaps similar relationships could be created, particularly with Asian countries. Almost half of survey respondents already export to the USA or Asia.

5.4 NURTURING A ROBUST INNOVATION ECOSYSTEM FOR HYDROGEN AND FUEL CELLS

The UK is much more likely to benefit economically from H2FC, and other novel technologies, if it can foster successful innovation ecosystems.

All innovation ecosystems are different, so there is no single approach to create a successful one while maximising the value of public investments. A successful system requires:

86 E4tech et al. (2019) Study on Value Chain and Manufacturing Competitiveness Analysis for Hydrogen and Fuel Cells Technologies.

87 Dodds P.E. (2015) Hydrogen and fuel cell technologies for heating: a review.

A VIBRANT INNOVATION ECOSYSTEM

Recommendation

Ensure there are mechanisms for UK researchers and companies to continue and build on existing collaborations with European counterparts, and access European markets.

- a sufficiently large skilled and innovative workforce;
- a diverse range of companies that interact both through competition and cooperation;
- sufficient funding and other support to underpin R&D;
- an appropriate regulatory and institutional framework; and,
- demand for products.

It is particularly challenging to encourage the development of an ecosystem for new technologies, especially when they are unlikely at first to be commercially competitive with incumbent options. For H2FC companies, the incumbent technologies that would be replaced benefit from market failures such as uncosted environmental externalities and standards and regulations designed for incumbents.

5.4.1 Opportunities and barriers to innovation in the UK

The industrial strategy is based on the premise that the UK has not been as successful at commercialisation and development as it has been at basic research. Identifying and addressing the underlying causes of this premise is not straightforward. Virtually all H2FC companies responding to our survey work with universities, which are generally well regarded by those companies, and two thirds of companies are exporters. Access to finance and the lack of a domestic market are considered the two key barriers.

Some companies, such as Ceres Power, have developed unique technologies that have secured foreign direct investment. If the UK can build critical mass across the H2FC sector, and particularly a strong knowledge and skills base, then large players are likely to make more general R&D-related investments into H2FC research in the UK so that they can benefit from that expertise.

The IEA has recommended establishing long-term targets, coordinating supply chains, strategic R&D and knowledge sharing, and harmonising standards and regulations.[88] Knowledge sharing has not been common practice in either academic research or innovation funding in the UK, at least until the recent drive towards open innovation and open access in academia.

5.4.2 Building a landscape of supportive institutions

Publicly-funded national energy labs often coordinate knowledge sharing in other countries, particularly in the USA. The UK has created a number of "Catapults", including several with an energy focus, but none have a focus on hydrogen and fuel cells. One possible option for supporting a stronger H2FC innovation system within the UK would be to establish and fund a dedicated innovation institution—outside

88 IEA (2019) The Future of Hydrogen: Seizing today's opportunities.

academia and with a strong business orientation—specific to H2FC technologies. The UKRI Research and Innovation Infrastructure programme has identified six potential research centres to develop various aspects of H2FC technologies in order to meet future UK needs (Table 3), which could be considered.[89]

Proposed centre	
1	Centre for the study of hydrogen use and safety of devices.
2	A facility to develop bulk production of low-carbon, low-cost, resilient hydrogen.
3	A research centre into the use of hydrogen in the gas grid, as an admixture or as 100% hydrogen.
4	A centre to research and develop the underground storage of hydrogen.
5	A research institute for fuel cells for the improvement of performance and reduction of cost.
6	A centre to facilitate the transition from a natural gas economy to a hydrogen economy.

Table 3. Ideas for H2FC research centres proposed by the UKRI Research and Innovation Infrastructure programme.

3 The Faraday Battery Challenge: a model for hydrogen?

The Faraday Battery Challenge is part of the UK Government's initiative to replace the internal combustion engine by 2035 and assist in its mission to electrify the economy. It is coordinated by UKRI through the EPSRC and Innovate UK, in collaboration with Advanced Propulsion Centre (APC). It has a 4-year initial funding commitment of up to £246 million from the Industrial Strategy Challenge Fund (ISCF), with a mission to develop and manufacture batteries for the electrification of vehicles and to help business seize low-carbon transition opportunities. The aim is to develop batteries that are cost-effective, high quality, durable, safe, low weight and recyclable. The challenge divides into research, innovation and scale-up, involving three parallel collaborative initiatives:

1. **Scale-up and manufacture:** an £80m UK Battery Industrialisation Centre delivered by APC, in collaboration with BEIS (via the ISCF), Coventry City Council, Warwick Manufacturing Group, and Coventry and Warwickshire LEPS. It brings together industry and academic expertise to create an institution operating with open-access principles, with the goal of assisting companies to develop their capabilities to manufacture the next generation of battery systems, get them to market, and scale-up for global exports.

2. **Collaborative R&D (£88m):** led by Innovate UK, for feasibility studies and collaborative research and innovation projects along directed themes that develop cost-effective new and improved battery technologies.

3. **Application-inspired fundamental research:** a £78m Faraday Institution funded through the ISCF. It is an independent institute with a remit to bring expertise together between academia and industry. It supports the other initiatives by establishing a battery technology training programme and funding a set of research challenge projects carried out by the academic sector under its direction.

89 UKRI (2019) The UK's research and innovation infrastructure: opportunities to grow our capability.

We examined the case for establishing a more general "Hydrogen and Fuel Cell Challenge" institution, along the model of the Faraday Battery Challenge (see Box 3). The existing literature provides a range of views about the appropriate design of innovation-support institutions, ranging from the USA's Advanced Research Projects Agency (ARPA) to Germany's network of Fraunhofer Institutes and the UK's Catapult centres. Key issues include the relative levels of public and private funding and control, the degree of autonomy from Ministers, and the timescales over which funding is committed.

To examine the case for a hydrogen-specific innovation institution, we interviewed a series of energy innovation experts, including former ministers, special advisers, civil servants, academics, and think tanks. Several interviewees had strong hydrogen-specific knowledge, and all had extensive experience of government-funded energy technology support programmes and policy. We asked the interviewees in particular to explore whether a model along the lines of the Faraday Battery Challenge might be appropriate for hydrogen, based on three core activities: (i) basic science research and skills; (ii) manufacturing-oriented support and R&D; and, (iii) support for business RD&D.

Our interviewees in general endorsed the desirability of establishing such mission-oriented innovation centres, built around clearly identifiable long-term goals, and with some degree of insulation from direct government control. In common with the research literature, our interviewees highlighted that a balance must be struck between independence from political interference, and a need to stay close enough to government to have influence and relevance to ongoing policy developments. Several—particularly those with a political background—highlighted the value that a hydrogen institution would have in terms of visibility for hydrogen energy technologies within government and more widely. A dedicated hydrogen innovation institution, outside academia, would act as a champion and hub for the wider technology area.

A key perceived challenge for such a centre is the diverse and highly uncertain application areas for hydrogen energy technologies. Unlike automotive batteries, which have a clear long-term industrial growth trajectory and a strong policy push behind electric vehicles, hydrogen energy is seen has having a less clear future. Our interviewees suggested that this makes the design and remit of a challenge-driven innovation institution more difficult for hydrogen than has been the case for automotive batteries. One approach would be to create a centre focusing on the future use of hydrogen in the energy system, including hydrogen production (excluding

A VIBRANT INNOVATION ECOSYSTEM

Recommendation

Consider creating a "Hydrogen Institute" focusing on the future use of hydrogen in the energy system.

A VIBRANT INNOVATION ECOSYSTEM

Recommendation

Consider creating an "Electrochemical Institute" to support fuel cell and electrolyser development, working closely with the Faraday Challenge.

electrolysers), storage, safety, combustion, industrial decarbonisation, synthetic fuels production, and pathways for developing hydrogen systems. A separate electrochemical centre could support fuel cell and electrolyser development, and work closely with the Faraday Challenge. Whatever approach is chosen would ideally strengthen links between basic and applied research in universities and companies, and address barriers such as the time needed to train engineers through PhDs to work in the H2FC sector.

5.4.3 Coordinating UK innovation

Each funder has different priorities and provides funding in different ways to achieve those priorities. Since developing truly novel, world-class technologies can be a 20-year process, having a mechanism to take a long-term view of innovation and investment needs in an area, and to provide coordination where necessary, is important. Research centres might fulfil such a role. The industrial strategy does not currently fund hydrogen and fuel cells as a sector, and has a focus on funding "waves" of short-term investments that would not necessarily be conducive to healthy innovation in these sectors in the long-term.

Another important part of an ecosystem is a two-way pipeline between basic research in universities and innovative activities in industry. The UK has substantial knowledge in H2FC across a range of universities, and links to companies are good and are considered to generally work effectively for H2FC. The industrial strategy has attempted to achieve collaboration by setting up academic centres alongside demonstration projects. One issue is that these themes run only for a short time, while there is a need for such links to evolve over long periods.

Public-private partnerships have been formed to accelerate innovation in some sectors by facilitating cross-sectoral engagement between industry and other stakeholders. For example, the Low Carbon Vehicle Partnership was created in 2003 to encourage a sustainable transition to low-carbon vehicles and fuels. More recently, the UK H2Mobility consortium was formed in 2013 to develop and share strategic insight into the commercial roll-out of hydrogen technologies in the transport sector. A broader "Hydrogen Partnership" would be valuable to enable industry, government and academia to work together to plan and implement a hydrogen economy in the UK over the coming decades.

It is not realistic for the UK to have a strong ecosystem in all areas. Public funding can either be spread thinly across many areas or focused to develop deep areas of excellence. The industrial strategy has taken a focused approach to date, but it is not clear that funding is designed with the health of ecosystems in mind, either in the short or long term. One challenge is that innovation ecosystems are not well understood. There is a case for developing methods to measure the health of innovation ecosystems, for example through the technology innovation system

A STRATEGIC VISION

Recommendation

Create a "Hydrogen Partnership" to accelerate a shift to hydrogen energy systems in the UK and to stimulate opportunities for UK businesses.

analysis or other emerging analytic tools (e.g. the Ecosystem Pie Model).[90] Section 3 has presented an alternative approach using a range of metrics for the H2FC sector as a whole, and which could be applied to specific areas within H2FC. An ecosystem analysis might identify support needs other than public sector funding support.

5.5 A STRATEGIC PLAN FOR THE DEVELOPMENT OF HYDROGEN AND FUEL CELL INDUSTRIES

A STRATEGIC VISION

Recommendation

Develop a hydrogen strategy for the UK to plan for a hydrogen economy, and identify opportunities to export both hydrogen technologies and green hydrogen fuel.shift to hydrogen energy systems in the UK and to stimulate opportunities for UK businesses.

A STRATEGIC VISION

Recommendation

Develop an electrochemical strategy that considers domestic and export opportunities for batteries, fuel cells and electrolyser innovations.

In 2016, Innovate UK published a UK H2FC roadmap[91] to strategically identify technology applications and steps to support technologies to commercialisation.[92] Given Innovate UK's role, this roadmap is aimed primarily at technology developments in the period from 2016 to 2025. It notes a need to better articulate the ramifications of H2FC being adopted in different ways in the long term. Such roadmaps are important for identifying short-term improvements and investments in technologies and manufacturing processes, which are required for technologies to outperform existing technologies, and become commercially-viable, in the long term.

The UK H2FC roadmap made a wide range of recommendations for various stakeholders, particularly focusing on the period to 2025, and it would be useful to create broader strategic visions for hydrogen and fuel cells that review, refresh, and broaden the scope of this roadmap to consider longer-term UK needs and how the hydrogen and fuel cell sectors could best be supported as a whole.

90 Talmar M. (in press) Mapping, analyzing and designing innovation ecosystems: The Ecosystem Pie Model.

91 Roadmaps are typically developed to identify pathways and actions to develop new technologies. Numerous roadmaps have been developed for hydrogen and/or fuel cells in various countries and regions.

92 E4tech and Element Energy (2016) Hydrogen and Fuel Cells: Opportunities for Growth

CHAPTER 6 - CONCLUSIONS AND RECOMMENDATIONS

INTRODUCTION

A number of H2FC technologies are on the cusp of being commercially viable. Fuel cells are moving from niche to mainstream markets, and very large markets for hydrogen are expected to emerge over the next two decades. An electrochemical industry has developed in the UK that is export-orientated and has attracted foreign direct investment.

FOSTERING UK MARKETS

A strong domestic market for fuel cells would enable a range of companies to expand their industrial activities and benefit from learning-by-doing and economies of scale. However, the UK market for fuel cells is very small compared to the global market. In the absence of public subsidies, there is not likely to be large market developing over the next five years in the UK. Moreover, since an existing market has been a requirement of industrial strategy funding to date, the support that might underpin the development of a market is not available either. UK companies identify the lack of a UK market as a key barrier to the growth of the UK H2FC industry. The UK has an opportunity to create an early market for low-carbon hydrogen in industry, heat provision, transport, and integration of renewable generation. We recommend considering four actions to underpin a market:

1. Use **public procurement, and subsidies** if appropriate, to create a market for fleets of fuel cell vehicles. A good approach would be to identify the best niches, for example for heavy duty vehicles, using business cases that account for the benefits of no air pollution and low noise.

2. Create a **national refuelling station network** for public and private use. It is difficult to justify the use of fuel cell vehicles if refuelling infrastructure is not available.

3. Examine opportunities to use **low-carbon hydrogen** in oil refining, ammonia and methanol production, steelmaking, and elsewhere, as part of the new ISCF industrial decarbonisation challenge.

4. Create a **green hydrogen standard scheme** for the UK to enable the value of green and blue hydrogen to be recognised by the market. A standard would use guarantee of origin certificates to demonstrate to customers that they were purchasing low-carbon hydrogen.

A STRATEGIC VISION

A strategic vision for hydrogen and fuel cells is needed to coordinate UK industrial development and innovation funding over the long term, and to introduce a more active engagement process. This strategy could build on the Innovate UK roadmap from 2016, but should ideally treat hydrogen and fuel cells separately, and consider opportunities to the year 2050. The strategy needs to balance domestic needs and export opportunities, and we recommend building on the Innovate UK sector roadmap by:

5. Developing a **hydrogen strategy** to plan for a UK hydrogen economy, and to identify opportunities to export both hydrogen technologies and green hydrogen fuel.

6. Developing an **electrochemical strategy** covering domestic and export opportunities for battery, fuel cell and electrolyser innovations.

7. In each strategy, **coordinating innovation funding** from UKRI and the UK Government, and how it is best invested between industry and academia, accounting for skills needs in the sector. While funding for hydrogen innovation has increased, funding for academic research into hydrogen and fuel cells has reduced to a low level.

8. Creating a "**Hydrogen Partnership**" to accelerate a shift to hydrogen energy systems in the UK and to stimulate opportunities for UK businesses.

A VIBRANT INNOVATION ECOSYSTEM

A strong H2FC sector requires a sufficiently large skilled and innovative workforce, a diverse range of companies that interact both through competition and cooperation, sufficient funding and other support to underpin R&D, an appropriate regulatory and institutional framework, and demand for products. Successful UK electrochemical companies have already secured substantial foreign direct investment. If the UK can build critical mass, and particularly a strong knowledge and skills base, then multinationals are likely to make more general R&D-related investments in the UK in order to benefit from that expertise. We recommend four actions:

9. Studying what would constitute **critical mass** in the hydrogen and fuel cell sectors, in terms of industry and academic capacity, and the skills and knowledge base, and considering whether the UK should invest to create a critical mass.

10. Consider creating a "**Hydrogen Institute**" focusing on the future use of hydrogen in the energy system, including hydrogen production (excluding electrolysers), storage, safety, combustion, industrial decarbonisation, synthetic fuels production, and pathways for developing hydrogen systems.

11. Consider creating an "**Electrochemical Institute**" to support fuel cell and electrolyser development, working closely with the Faraday Challenge.

12. Ensure there are mechanisms for UK researchers and companies to continue and **build on existing collaborations with European counterparts**, and access European markets, given the importance of these to the sector.

The view of UK H2FC companies is that the UK is falling behind other regions of the world. These trends suggest that the UK is at risk of losing out on commercial opportunities associated with H2FC technologies in the future. Public support is required to nurture a domestic market and underpin innovation. With the right support, the UK has the potential to develop a strong hydrogen and fuel cell industrial sector to meet future energy demands, both at home and abroad.

H2FCSUPERGEN
THE HYDROGEN AND FUEL CELL RESEARCH HUB

This paper has been commissioned by the UK Hydrogen and Fuel Cells Supergen Hub to examine the opportunities for hydrogen and fuel cell technologies to contribute to clean growth. It assesses the strength of the UK hydrogen and fuel cells sector using a range of metrics and recommends actions to underpin the development of a substantial export-focused industry.

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