THE ROLE OF HYDROGEN AND FUEL CELLS IN PROVIDING AFFORDABLE, SECURE LOW-CARBON HEAT

A H2FC SUPERGEN White Paper

Executive summary

May 2014
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BACKGROUND

This White Paper has been commissioned by the UK Hydrogen and Fuel Cell (H2FC) SUPERGEN Hub to examine the roles and potential benefits of hydrogen and fuel cell technologies for heat provision in future low-carbon energy systems.

The H2FC SUPERGEN Hub is an inclusive network encompassing the entire UK hydrogen and fuel cells research community, with around 100 UK-based academics supported by key stakeholders from industry and government. It is funded by the UK EPSRC research council as part of the RCUK Energy Programme. This paper is the first of four that will be published over the lifetime of the Hub, with the others examining: (i) low-carbon energy systems (including balancing renewable intermittency); (ii) low-carbon transport systems; and, (iii) the provision of secure and affordable energy supplies for the future.

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HEADLINE MESSAGES

Fuel cell CHP is already being deployed commercially around the world. Commercial and industrial enterprises have used fuel cell CHP for decades, particularly in the USA. Meanwhile, sales of residential micro-CHP units are doubling every year, and in Japan they will be fully competitive (sold without subsidy) from 2015. The capital costs of fuel cells have greatly reduced in recent years as a result of innovation and learning through field trials and deployment programmes.

Hydrogen can be a zero-carbon alternative to natural gas. Most technologies that use natural gas can be adapted to use hydrogen and still provide the same level of service. Hydrogen could potentially be delivered via the existing natural gas distribution networks, although more research is required to fully understand the issues surrounding conversion of the networks. In the shorter term, injecting small amounts of hydrogen into the gas networks or producing synthetic natural gas using hydrogen and waste CO₂ effluent could reduce the emissions intensity of the gas delivered to all users.

Hydrogen and fuel cells are part of the cost-optimal heating technology portfolio in long-term UK energy system scenarios. Most heat decarbonisation studies have considered neither hydrogen as a fuel for heating nor fuel cell CHP as a low-carbon heating technology. Only three of twelve studies that have informed UK energy policy have examined these technologies and two of them identify a cost-optimal role for hydrogen. Notably, only these two studies consider the economic benefits of converting the existing gas distribution networks to deliver hydrogen.

Hydrogen and fuel cell technologies avoid some of the disadvantages of other low-carbon heating technologies. Current heat pump technologies can be broadly characterised by high capital costs, sensitivity to operating conditions and large space requirements. In contrast, hydrogen boilers could provide zero-carbon heat without such disruptions to living patterns while being affordable for households. Fuel cell systems are currently a similar size and cost to heat pump systems, but smaller wall-mounted versions are under development and capital costs are falling rapidly.
Fuel cells can support the integration of renewables and other low-carbon technologies into the electricity system. Peak electricity demand coincides with peak heat demand in the UK. Field trials of micro-CHP fuel cells show that they generate electricity when it is needed most by the grid. Electric vehicles and heat pumps will increase peak demand, while building more intermittent renewable generation will increase the supply variability. Additional peaking plant capacity will be needed to cope with both trends. Fuel cell CHP can make an important contribution to meeting peak demand while also diversifying and decentralising electricity generation, increasing the national security of supply.

Some government policies penalise hydrogen and fuel cell technologies compared to alternative low-carbon technologies. For example, the current definition of “good quality” CHP should be reviewed as stakeholders feel that the existing treatment of fuel cell CHP is discriminatory. More generally, CHP incentives do not reflect the value of fuel cells for supporting peak electricity generation and avoiding network reinforcement. Policies addressing market failures for low-carbon technologies do not generally extend to hydrogen and fuel cell technologies, despite fuel cells being successfully supported towards commercial maturity abroad.

Hydrogen and fuel cells are habitually excluded or marginalised in technology innovation needs assessments and heat policy papers. These tend to concentrate on a small number of technologies and identify hydrogen and fuel cell technologies for future research rather than near-term demonstration and deployment. Yet programmes such as converting the gas networks to deliver hydrogen would require government direction and the costs could be greatly reduced through the early development of a roadmap to identify and address the technical challenges.

The UK has an opportunity to develop a hydrogen and fuel cell industry for heating. The UK has a strong scientific base in hydrogen and fuel cell research. A number of UK-owned and UK-based firms are international leaders in hydrogen and fuel cell technologies. The sector also includes globally-established suppliers of components as well as a number of innovative new entrants developing novel technologies and components. Support at home would enable UK companies to capture a share of fast-growing global supply chains for hydrogen and fuel cell heating technologies.
1. THE CHALLENGE OF LOW-CARBON, SECURE, AFFORDABLE HEATING

Almost half of all UK energy consumption is used for heating in homes, offices or industry, mainly with natural gas. Since the UK has committed to reducing its greenhouse gas emissions by 80% by 2050 compared to 1990, a low-carbon alternative will be required to reduce the emissions from heating. The search is on for low-carbon heating alternatives to natural gas that are affordable for households and businesses and for which there is security of supply.

The electrification of heat provision, using efficient heat pumps, is one possible alternative, as are solar heating and biomass. Fuel cells and other hydrogen-fuelled technologies have so far received little attention in this regard but could potentially generate low-carbon heat, as well as electricity for combined heat and power (CHP) technologies, while avoiding some of the disadvantages of other low-carbon technologies.

Figure ES1 Cumulative number of fuel cell micro-CHP systems deployed in three major regions, showing historic growth (solid lines) and near-term projections (dotted lines)

Fuel cells are already being used for heat provision in other countries. Fuel cell CHP has been deployed for commercial and district heat-scale technologies for several decades. Smaller micro-CHP fuel cells are now being deployed commercially in Japanese houses and programmes are underway in several other countries, supported by both governments and industry. The number of micro-CHP fuel cells has
been doubling each year in several countries and Japan has a target for 1.4 million to be installed by 2020 (Figure ES1). European deployment is predominantly in Germany at present.

This paper assesses potential roles for hydrogen and fuel cells in low-carbon heating. It reviews the science of and identifies potential markets for fuel cell CHP and other hydrogen-fuelled technologies. It examines the possible benefits of these technologies from the perspective of the whole energy system, with a focus on residential fuel cell CHP in particular. Finally, it identifies the UK industrial strengths in hydrogen and fuel cells, and considers policy issues that will need to be addressed to give these technology options a level playing field with other low-carbon heating technologies.

2. THE SCIENCE OF HYDROGEN AND FUEL CELL CHP

Fuel cells for combined heat and power (CHP)

Stationary fuel cell CHP technologies use hydrogen or other fuels to generate both heat and electricity, the latter of which may be used directly or fed into the electricity grid. Hydrogen is not the only fuel that can power fuel cells and most are not directly fuelled using hydrogen at the moment, partly because of difficulties with distribution and storage. Natural gas is most widely used along with LPG (liquid petroleum gas) and biogas, and these are converted into hydrogen within the fuel cell system. While fuel cell-powered vehicles have received much attention in recent years, stationary applications are currently the largest commercial market for fuel cells.

The operation and characteristics of fuel cells

Fuel cells convert the chemical energy in a fuel directly into electrical current and heat without combustion. They are a modular technology that can be scaled up from serving individual homes to large office blocks and industrial complexes. CHP is the most common stationary application for fuel cells and currently provides their largest and most established market. By capturing the heat produced in the fuel cell, and distributing it to the building or process, overall fuel use efficiencies of up to 95%\(^1\) can be achieved, while also generating decentralised electricity and reducing CO\(_2\) emissions.

Just as there are different types of battery, many fuel cell technologies have been developed which use different means to achieve the fundamental electrochemical reaction. These technologies use very different sets of materials and operate at different temperatures, which affect the fuels they can tolerate and the peripheral equipment they require; however, they all share the characteristics of high efficiency, few moving parts, quiet operation, and low emissions at the point of use.

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1. Following European convention, all efficiencies in this White paper are expressed relative to the lower heating value (LHV) of the fuel input. To convert from lower to higher heating value (HHV) for natural gas, divide these efficiency values by 1.109.
The different kinds of fuel cells are summarised in Table ES1 and their technical characteristics are compared in Table ES2.

**Table ES1 Fuel cell technologies for CHP applications**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Type</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEMFC</td>
<td>Proton Exchange Membrane</td>
<td>Used for most installed residential micro-CHP systems</td>
</tr>
<tr>
<td>SOFC</td>
<td>Solid Oxide</td>
<td>Large industrial CHP and residential micro-CHP systems</td>
</tr>
<tr>
<td>MCFC</td>
<td>Molten Carbonate</td>
<td>Large industrial CHP and grid-scale electricity production</td>
</tr>
<tr>
<td>PAFC</td>
<td>Phosphoric Acid</td>
<td>Used since the 1970s in commercial-scale CHP systems</td>
</tr>
</tbody>
</table>

**Table ES2 At-a-glance summary of fuel cell performance**

<table>
<thead>
<tr>
<th></th>
<th>PEMFC</th>
<th>SOFC</th>
<th>PAFC</th>
<th>MCFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Residential</td>
<td>Residential/Commercial</td>
<td>Commercial</td>
<td></td>
</tr>
<tr>
<td>Electrical capacity (kW)</td>
<td>0.75–2</td>
<td>0.75–250</td>
<td>100–400</td>
<td>300+</td>
</tr>
<tr>
<td>Thermal capacity (kW)</td>
<td>0.75–2</td>
<td>0.75–250</td>
<td>110–450</td>
<td>450+</td>
</tr>
<tr>
<td>Electrical efficiency* (LHV)</td>
<td>35–39%</td>
<td>45–60%</td>
<td>42%</td>
<td>47%</td>
</tr>
<tr>
<td>Thermal efficiency* (LHV)</td>
<td>55%</td>
<td>30–45%</td>
<td>48%</td>
<td>43%</td>
</tr>
<tr>
<td>Current maximum lifetime</td>
<td>60–80'000 hours</td>
<td>20–90 years</td>
<td>80–130 years</td>
<td>20 years</td>
</tr>
<tr>
<td>Degradation rate† (Per year)</td>
<td>1%</td>
<td>1–2.5%</td>
<td>0.5%</td>
<td>1.5%</td>
</tr>
</tbody>
</table>

* Rated specifications when new, which are slightly higher than the averages experienced in practice. † Loss of peak power and electrical efficiency; thermal efficiency increases to compensate. ‡ Requires an overhaul of the fuel cell stack half-way through the operating lifetime.

The economics of fuel cells

The high capital costs of fuel cells are the major hurdle to their economic viability. Fuel cells are still more expensive than competing technologies, but this gap is rapidly narrowing as the technologies mature. Figure ES2 shows the price trends of fuel cells in Japan and South Korea in recent years. Prices of residential systems have fallen
dramatically – by 85% in the last 10 years in Japan, or by 20% for each doubling in cumulative production in Japan and Korea. However, as seen in Figure ES2, the price of Japanese systems has fallen more gradually since their commercialisation in 2008.

**Figure ES2 Experience curves fitted to the historic price of EneFarm (Japan) and South Korean residential PEMFC systems from the last ten years**

The main means through which future capital cost reductions at all scales may be achieved are:

- reducing system complexity through design optimisation;
- eliminating major system components such as fuel processing stages;
- cell-level design improvements such as reducing catalyst content and increasing power density;
- greater collaboration between manufacturers to standardise minor components and overcome research challenges more effectively; and,
- further expansion of manufacturing volumes and mass production techniques.

The high capital cost of fuel cell systems is at least partially offset by lower running costs which result from lower consumption of grid electricity. Figure ES3 demonstrates the financial savings from running a 1 kW PEMFC in an average British household today. The reduction in grid electricity purchases is almost offset by increased gas
consumption; however, excess electricity production can be exported for 4.77 p/kWh, and the UK government’s feed-in tariff (FiT) for micro-CHP currently pays 13.24p for each kWh of electricity generated. Together these give annual revenues of £774, allowing fuel cell owners to reduce their energy bill by two-thirds in the current policy climate. However, the majority of this saving is from FiT subsidies at present; in the long term, fuel cell CHP competitiveness relies on further reducing capital costs and on the income from electricity generation fully reflecting the benefits to the electricity system, as discussed below.

**Figure ES3** Breakdown of annual energy bills for an average UK house with PEMFC micro-CHP and conventional gas heating (see main report for details)

The economics of commercial and industrial CHP need to be better than for residential as they must offer an attractive payback period to gain sales. The annual expected return on investments (ROI) for CHP ranges from 8–16% in the UK, depending on the customer and their energy costs.

**The environmental implications of fuel cells**

Fuel cell systems are larger and heavier than the gas boilers they replace, and require catalyst metals such as nickel and platinum which are extremely energy-intensive to produce. Just as with other low-carbon technologies (e.g. solar PV and nuclear), the energy required to manufacture the fuel cell compared to alternatives, and the resulting carbon emissions, are important as these offset the savings made during operation. The carbon intensity (gCO₂/kWh) of
fuel cell construction is estimated to be comparable to that of nuclear power stations and lower than that of solar PV.

In operation, fuel cells using natural gas can reduce carbon emissions relative to conventional heating technologies as they reduce the amount of electricity that needs to be generated centrally, which in most countries has a high carbon intensity. CO₂ savings from fuel cells are therefore country- and site-specific, depending on the carbon intensity of grid electricity and on the heating system that is displaced. In the UK, a residential fuel cell heating system fuelled by natural gas currently reduces the annual CO₂ emissions from the average household by approximately 1–2 tCO₂.

Emissions of other air pollutants, for example oxides of nitrogen (NOₓ), carbon monoxide (CO) and particulates (PM₁₀), are around a tenth of those from other gas-burning technologies.

**Hydrogen for heating**

Until the conversion of households to natural gas from the North Sea in the 1970s, hydrogen was piped to many UK homes as the largest constituent of town gas. Hydrogen can be used as an alternative to natural gas for space heating, water heating, and for gas cooking. Because the physical properties of hydrogen differ from natural gas, switching from natural gas to hydrogen heating would require changes to the gas network and to heating and cooking appliances.

Hydrogen may be burned directly in boilers, for individual household or commercial applications, or even for district heating. Novel types of hydrogen boilers are under development. Hydrogen may also be directly used in fuel cells, as already discussed. Gas heat pumps, which are already commercially available in some countries for household or commercial use, and have much higher efficiencies than gas boilers, may also be converted to hydrogen.

There is no fundamental difference in the appearance or operation of hydrogen gas boilers when compared to their natural gas equivalents. Hydrogen can be combusted in a combi-boiler and therefore requires no additional space in the household, in contrast to other low-carbon technologies. Hydrogen boilers are also much cheaper than alternatives such as heat pumps.

**Production and delivery of hydrogen**

Like natural gas, the widespread use of hydrogen gas would require its transmission and distribution through pipeline networks, and facilities for storage. A small number of high-pressure pipelines to transport hydrogen between industrial producers and consumers
already exist. However, widespread use of hydrogen for heating in the UK would require huge quantities to be produced and distributed. The natural gas transmission network is not suitable for transporting hydrogen, so, if hydrogen transmission were required, a new dedicated transmission network would have to be constructed, which could serve both transport and heat markets. Yet there is a possibility of converting the existing low-pressure distribution networks to deliver hydrogen in the longer term, and these comprise the vast majority of the gas system. In the near term, hydrogen could be injected into the natural gas distribution networks without a conversion programme, to lower the carbon intensity of the delivered gas. It is thought that the network could accommodate at least 10% hydrogen by volume while existing appliances could use gas with 3% hydrogen without requiring modification, although there are complexities and caveats around these figures which are explored in more detail in the main paper. Of course, a conversion programme would also need to achieve public acceptance of the safety of hydrogen use in homes.

Hydrogen is currently used in a wide variety of industries and can be produced either locally or at large central plants from biomass, natural gas, coal, waste or by electrolysis of water. Current hydrogen production is largely from natural gas but future methods would need to produce low-carbon hydrogen, such as by electrolysis water with zero-carbon electricity or by using fossil fuels with carbon capture and storage technologies. Accounting for the lower volumetric energy content of hydrogen, in order to completely replace current UK requirements for natural gas on an energetic basis using indigenous capacity, UK hydrogen production would need to increase by a multiple of 20–35 times above existing levels.

3. POTENTIAL UK HEATING MARKETS FOR HYDROGEN AND FUEL CELLS

The UK spends £32bn on heating each year, including around £1.7bn on heating products. Under the influence of government policy, as discussed further below, a UK market for low-carbon heating is gradually emerging. In the markets for space and water heating, hydrogen and fuel cell technologies face competition from several established and emerging technologies: condensing gas boilers, biomass boilers, engine-based CHP, electric and gas-engine heat pumps, solar water heating and district heating via heat networks.

The UK has four main heat markets. Prospects for the adoption of hydrogen heating and fuel cell products are examined in each of these in turn.
Residential heat markets

Residential sector fuel consumption for space heating, water heating and cooking accounts for around half of the total UK heating fuel consumption. Heating demands vary substantially between households, as shown in Figure ES4, with large detached houses consuming around six times more fuel for heating than small flats. Demand is highly seasonal with a winter peak that is on average around seven times the average summer consumption.

Figure ES4 Variation in household heat demand between classes of housing for an average year

Heat demand includes space and water heating. Winter consumption is strongly temperature-dependent and the winter peaks can be much higher in a cold year.

British consumer preferences regarding heating systems show a strong cultural affinity for gas boilers, which are perceived as safe, cheap, effective and easy to control. They therefore represent a strong incumbent technology, which is likely to prove difficult to displace with alternatives other than perhaps similar hydrogen-fuelled boilers. There is some evidence that micro-CHP is slightly more attractive to consumers than other low-carbon residential heating system technologies, but all such technologies suffer from the consumer preference for natural gas-based heating systems (except fuel cell micro-CHP, which can be gas-fuelled), the lack of a strong mass market demand for energy efficiency measures and alternative heating products, cost factors, and weaknesses in the UK supply chain for such products, including hydrogen and fuel cells. There are neither retail channels for purchasing these technologies nor qualified installers who can put units in homes.
Hydrogen-fuelled technologies are a long-term option as there is no delivery system at present, although hydrogen injection into the existing gas grid offers one possible route for utilising hydrogen with existing natural gas appliances.

Micro-CHP fuel cells, on the other hand, could be deployed now. They are packaged as complete heating systems, with a fuel cell integrated with a boiler and hot water tank. They are typically installed outside in the UK and Japan, which could impact the visual appearance of a property, although wall-hanging models are under development. Fuel cell micro-CHP technologies are smaller than most low-carbon alternatives. While still five times the installation cost of residential gas boilers (fuel cells cost around £12,000 for 1 kW residential systems, but these costs are falling 10–15% per year), fuel cells are beginning to compete with other low-carbon heating technologies and their running costs are lower, even without public policy support. While fuel cells are larger and heavier than conventional boilers, their size is comparable or smaller than that of most other low-carbon technologies. Their installation is relatively simple and they operate as quietly as condensing gas boilers. Only a few fuel cells have been tested to date in the UK and larger-scale field trials would help to lower production costs while developing a supply chain to support commercial deployment.

Around 1.5m household boilers are replaced each year. Apart from distress purchases involving the replacement of broken or malfunctioning boilers, heating system replacement is generally only considered by householders as part of wider renovation works. Only around 1 in 10 consumers are interested in carrying out changes to their living environment to make it more energy efficient, with the vast majority making decisions based on cost and amenity factors such as aesthetics and the use of space. Because of the premium put on space, shown by the rapid uptake of combination (combi-) boilers in Britain and the removal of the hot water storage tanks associated with the older systems, heating systems that involve the loss of previously usable space, like many micro-CHP or heat pump configurations, may prove unpopular where space is at a premium.

**Commercial and public sector heat markets**

UK commercial and public sector fuel consumption for heating is around 20% of the total heating fuel consumption. As with the residential sector, space and water heating are the largest energy demands, with 72% of commercial sector businesses currently heated by gas, and electricity and oil comprising most of the remainder. Around 20,000 commercial boilers are believed to be sold each year.
Commercial premises vary much more significantly than homes in terms of their size, shape, and level of heat demand. Some larger commercial properties, particularly those with high heat demands such as hotels, hospitals and leisure facilities with swimming pools provide a potential market for fuel cell CHP. Larger premises tend to have a more steady demand for heat and power than individual homes so are better suited to fuel cells, while critical facilities such as hospitals and data centres also have a key requirement for high reliability backup power that can also be met by fuel cells. Medium-scale (200–400 kWe) fuel cell CHP systems that provide heat, electricity and sometimes also cooling have been installed in several buildings in the UK.

At around £1m for 400 kW commercial systems, the costs of fuel cell CHP are between 2.5 to 20 times higher than gas-engine CHP, although as already noted fuel cell capital costs are decreasing and lifetimes increasing, and this may ultimately serve to change the status quo. In addition, within the commercial sector, fuel cell products are enjoying a degree of success in electricity-only applications such as the provision of standby power. The growth of this market may result in cost reductions that make fuel cells more cost-competitive with other technologies, which may increase their use in heating applications such as CHP.

Industrial heat markets
While around 30% of the UK’s fuel consumption for heating comes from industry, industrial plants tend to have specific requirements for the flow rate, temperature and pressure of delivered heat. While hydrogen could substitute for natural gas in many processes, the potential market for fuel cell CHP is smaller, but it is not insignificant. Indeed, by-product hydrogen is already used as a heating fuel in some UK industrial plants such as the INEOS plant in Runcorn.

As with the commercial sector, technological immaturity and resulting high costs are major barriers to the uptake of hydrogen and fuel cell products. However, hydrogen may be a useful substitute for a number of processes that are currently fossil-fuelled. Industrial by-product hydrogen may offer a potential early market niche for hydrogen and fuel cell technology within industry, while another potential industrial niche is energy from waste facilities. Low-temperature industrial heat is also a large and untapped market that larger PAFC and MCFC systems could move into, providing low-grade heat, while large SOFC systems can provide process heat at up to 1000 °C, and so could be used to decarbonise a wider range of industrial facilities, if they became cost-competitive.
District heating markets

District heating schemes currently represent only a very small part of UK heat demand, but there are plausible scenarios for them to supply as much as 40–50% of UK heat demand by 2050, and the Government in recent years has consistently expressed support for district heat network development. Hydrogen heating systems and fuel cell CHP technologies could be used to supply energy for heat networks, either within a single apartment block or as part of a wider heat network. Using hydrogen for district heat may reduce safety concerns about piping hydrogen into houses.

District heating faces a number of significant barriers to widespread deployment in the UK. As with the other sectors, barriers to the deployment of fuel cells in district heating include high costs relative to incumbent technologies and the lack of a robust UK supply chain. Fuel cells are also unfavourably treated compared to other CHP technologies, as discussed below. In the longer term, hydrogen could develop as a substitute for natural gas in the supply of thermal energy to heat networks.

4. HYDROGEN AND FUEL CELL HEATING SYSTEMS

Modelling future heat provision by hydrogen and fuel cells

A number of models have been used to study scenarios of UK energy system decarbonisation. Many of these studies have identified decarbonisation of the electricity supply as a key early goal, alongside a mass-market shift in transport and heating towards low-carbon alternatives. The cost-optimal pathway for heat is often electrification, using heat pumps, combined with an ambitious programme of energy efficiency measures such as thermal insulation.

However, most of these models consider a similar mix of low-carbon technologies that excludes both hydrogen and fuel cell CHP. Only three of the reviewed models – RESOM, UK MARKAL and UKTM-UCL – consider a wide range of heat technologies that include hydrogen and fuel cells. Conversion of the gas networks to deliver hydrogen has only been assessed using UK MARKAL and UKTM-UCL. The UK MARKAL study concludes that using fuel cells powered by hydrogen from a converted gas network could be the lowest-cost option for decarbonising heat, reducing the number of houses using heat pumps while supporting heat pump operation through high electricity as well as heat output at peak demand times. The new UKTM-UCL model also finds a cost-optimal role for hydrogen technologies in the same scenario, but for hydrogen-fuelled boilers rather than fuel cell CHP.
These studies show that hydrogen and fuel cell technologies could have a role in future heat provision but that this depends on a number of factors, particularly the relative prices of electricity and hydrogen. The levelised costs of heat provision are reasonably close for a number of technologies and further research is required to understand the impact of uncertainties in these costs and in commodity prices. Although most of the UK uses a single technology for heating at present (gas boilers), most scenarios of the future forecast a portfolio of different technologies being used in different houses. Particularly when non-economic characteristics are taken into account, none of the low-carbon technologies are clearly superior to the others and it is not clear that any one technology should be prioritised. Heat provision is similar to electricity generation in this regard, where a portfolio approach is being used to support new technologies, and a similar inclusive approach to all technologies, including hydrogen and fuel cells, seems appropriate for heat provision.

**Case studies of residential micro-CHP**

The UK energy system is expected to change radically over coming decades, with developments such as significant shares of wind and nuclear power entering the UK electricity system posing new challenges in terms of system flexibility and the provision of capacity to reliably serve peak demand. Heat decarbonisation, as part of the system transition, offers great opportunities and challenges. The range of applications of heat as an energy vector represents a very substantial portion of national final energy demand, and as such any changes in the way it is delivered can have very significant financial and infrastructure impacts, particularly given the scale of seasonal and diurnal swings. However, heat demand is also relatively flexible, with possibilities for storage, demand side management, and use of ‘linepack’ in district heating all offering valuable flexibility. Four case studies examining the role of fuel cell micro-CHP in supporting and interacting with future energy systems are presented.

During a cold winter weekday, heat and electricity demand is reasonably well correlated in the UK, as shown for an aggregated sample of 2,700 households in Figure ES5. Therefore, fuel cell CHP, by providing heat and power simultaneously, is naturally well matched to serving residential sector demand and may have an important role to play in supporting broader electricity system operation in the future, as well as reducing CO₂ emissions. The role of fuel cells alongside other technologies, and as part of a wider low-carbon energy system, is explored here for micro-CHP applications with heat to power ratios ranging from 1:1 to 2:1 (i.e. as would be expected of fuel cell systems), using empirical field trial data and simulation modelling at high temporal resolutions.
The first case study considers the contribution of micro-CHP fuel cells to meeting peak winter electricity demand. CHP is a heat-led technology, in that it is controlled to match heat demand. As shown in Figure ES5, peak heat demand occurs at approximately the same time as peak electricity demand. Therefore, CHP electricity output is likely to occur at a time when it will displace the need for additional network and generation capacity. The case study calculates that each kW of fuel-cell based CHP electricity generating capacity in this simulation would obviate the need for around 0.6 kW of peak capacity requirements. Total system savings in excess of 500 £/kW of installed fuel cell capacity could be realised from this.

**Figure ES5** Aggregated thermal and electrical power demands from 2700 dwellings in the UK on a winter weekday

The second case study explores the potential of fuel cells to complement heat pumps for residential heat applications, as well as their potential match with likely charging patterns for electric vehicles. As micro-CHP and heat pumps are both operated to provide heating, the system impact of heat pumps on the electricity network could be mitigated by complementing heat pumps with micro-CHP technologies. Figure ES6 shows the impact on the load duration curve of the low-voltage network from combining fuel cell micro-CHP with heat pumps (where they are located close together and on the same phase in the distribution network). The Baseline gives the current profile of the curve, with heating mainly supplied by gas boilers. The hours of duration of high loads are shown at the left hand side of the diagram – the Baseline shows that for about 500 hours there are loads of more than 20 kW from these houses. Fitting 20% of dwellings with heat
Executive summary

Pumps increases the power load substantially across the period measured, and the peak load rises to more than 50kW. However, adding fuel cells, which generate electricity during peak demand periods, to 50% of households as well almost completely offsets the extra peak demand from the heat pumps, thereby deferring reinforcements and upgrades that would otherwise be necessary. A similar outcome can be observed with respect to the interaction of fuel cell CHP and the electrification of transport, with CHP output offsetting peak demand impacts of battery electric vehicle charging.

Figure ES6 Load duration curve for a group of 46 dwellings

Complementing 20% heat pump penetration with 50% adoption of fuel cells (the remaining 30% of heating systems are assumed to be gas boilers) can mitigate increased peak demand during winter peak periods.

The third case study assesses the comparative performance of fuel cell and Stirling engine CHP systems, with the same electrical capacity, in homes of different thermal efficiency. The results show that fuel cells generate more electricity than Stirling engines in more efficient homes (i.e., with lower heat demands). This is because they have a lower heat-to-power ratio, and can therefore continue to operate when heat demand is low, while higher heat-to-power ratio systems must modulate or switch off (subject to the availability of thermal storage capacity). This means that fuel cell micro-CHP has more potential to continue to be viable in future housing stocks with much improved thermal efficiency.

The fourth and final case study examines the relative carbon intensity of three residential heating technologies: condensing boilers, heat...
Condensing boilers only use gas, and so their emissions are unaffected by the electricity CO₂ intensity; heat pumps use electricity, so their emissions rise with its CO₂ intensity; fuel cells displace grid electricity, so their net emissions fall the higher the CO₂ intensity of the electricity grid. As shown in Figure ES7, fuel cell based CHP systems have the lowest CO₂ emissions over the heating season out of these three technologies, so long as grid marginal emissions remain above 0.33 kgCO₂/kWh.² The lower grid emissions become, the less natural gas-fuelled fuel cells are able to offset their own emissions by displacing grid emissions.

**Figure ES7 Comparison of CO₂ emissions by technology for different marginal grid emission factors**

For comparison, the CO₂ emissions factor of natural gas is 0.189 kgCO₂/kWh.

The key conclusions from the four case studies are that fuel cell CHP:

- can provide substantial system benefits in terms of reducing peak electricity demands on the central electricity system;
- is complementary with other electrically-powered decarbonisation technologies (e.g. heat pumps and electric vehicles) and could mitigate their potentially significant local network integration costs, where a portfolio of technologies are used locally;
- is resilient against future reductions in building thermal demand in terms of performance; and,
- could be competitive in CO₂ terms well into the future, if not indefinitely if fuel sources are decarbonised.

² The CO₂ intensity of UK electricity in 2010 was about 0.5 kgCO₂/kWh.
5. INDUSTRIAL CAPACITY AND POLICY ISSUES

**The UK hydrogen and fuel cell industry**

The UK has a strong scientific base in hydrogen and fuel cell (H2FC) research; it is within the top 10 countries globally in terms of numbers of hydrogen and fuel cell publications and second only to Germany in terms of average citations per article.

However, the UK’s capacity for commercialisation of new technologies is more modest. One measure of the UK’s capacity to generate H2FC-related inventions is data on patents. Figure ES8 shows that the UK has a relatively small share of global PCT (Patent Cooperation Treaty) patents in these technologies, lying well behind Japan, the US and Germany.

**Figure ES8 Relative shares of global patents based on PCT patents from World Intellectual Property Organisation (WIPO)**

Note the relative growth of Japan against both Germany and the US.

Data on the relative specialisation of different countries in H2FC technologies, as measured by ‘revealed patent advantage’, has a similar trend. Even so, the UK is in the top ten countries globally in terms of fuel cell patents granted. It is notable that in leading competitor countries (US, Germany, Korea and Japan) the dominant patent filing firms are major industrial players: GE, Siemens, Samsung and Panasonic, as well as firms for whom fuel cells are the core business. The UK fuel cell industry lacks a large firm such as these.

Overall levels of public R&D spending on energy in the UK are much lower than many competitors, but the share of public R&D that is devoted to H2FC in the UK is comparable to most competitor countries, all major public energy R&D funding bodies providing support to various H2FC projects. However, financing for demonstration of H2FC
technologies in heating applications, which is critical to enable the establishment of a commercial market and supply chains, is more difficult to access, and is so far largely supported at the European level. There are also perceived problems with the ability of UK firms to raise capital. Skills, in contrast, are not overall seen as a major stumbling block for the growth of a UK hydrogen and fuel cell industry. Overall, while there are some good examples of UK-owned firms with excellent products in the H2FC market, and very productive R&D activities, the UK is still not a leader in the market in terms of size and diversity.

Globally, more than 30 MW of new stationary fuel cells have been installed every year since 2007, with over 100 MW deployed in 2012 alone as shown in Figure ES9 (including both CHP and power-only applications). Much of this growth has occurred in Asia and new markets are expected to develop in Europe and the USA as well, as fuel cell costs continue to fall. Estimates of the potential global market vary enormously, and such estimates are of course highly uncertain, but recent progress in cost reduction and extensions of policy support in key markets have secured continued growth in the short term while bolstering the long-term potential.

In the UK, the rate of market development is very much lower than it has been in Japan, Korea and the US, with less than 2 MW of stationary fuel cells deployed in total. The slow uptake of fuel cell technologies in the UK as compared to other jurisdictions is due to weak policy support in the UK, with less funding for demonstration projects and weaker support for deployment.

**Figure ES9** Annual global deployments of fuel cells in stationary applications

![Graph showing annual global deployments of fuel cells in stationary applications](image)

Note: includes power-only as well as CHP applications.

Source: Fuel Cell Today
Heat policy issues

Despite comprising almost half of UK energy consumption, heat has only recently become prominent in energy policy discussions. However, although hydrogen does feature in the government’s vision for the future of heating, a recent heat policy projection does not include H2FC technologies.

UK heat policy, like energy policy more generally, has the overall, potentially conflicting, objectives of decarbonisation, energy security and energy affordability and is also informed by the desire to stimulate the development of technologies with opportunities for exports or import substitution. Subsidiary policy objectives are to promote renewable energy and energy efficiency, and technologies that yield system benefits. In general, market intervention is only considered where there are perceived to be market failures, or where infrastructure lock-in leads to undesirable outcomes.

In this complex environment four general rationales for measures to support hydrogen and fuel cells in heating are widely expressed: (i) that policy should treat these technologies comparably to others; (ii) that market arrangements should reward system benefits; (iii) that low-carbon heating options should be kept open; and, (iv) that opportunities for industrial development should be taken. These issues are summarised here.

With regard to comparable treatment, current policy mechanisms provide support for heating technologies or fuels where they are lower-carbon (via technology-neutral measures) or use renewable fuel, as well as providing specific support for CHP (including micro-CHP). There are no current incentives dedicated to hydrogen and fuel cell technologies except where they fit into the above categories. In particular, hydrogen and fuel cell technologies are not directly eligible for support under the recently introduced renewable heat incentive (RHI) because neither hydrogen (as an energy vector) nor fuel cells (as conversion devices) are inherently renewable, although fuel cell systems are eligible for support where the fuel is a renewable fuel, and hydrogen-rich gases produced from biomass are eligible where these are produced by anaerobic digestion, pyrolysis or gasification. However, hydrogen produced from renewable electricity is not eligible, and in any case incentive mechanisms exist for the production of electricity from renewable sources.

A range of policy incentives provide support for CHP, including fuel cell CHP and combustion-based CHP using hydrogen as a fuel. However, these incentive and support structures treat fuel cells unfairly, especially through the CHP QA quality assurance process and
the exclusion of fuel cells from the national database of operational CHP projects, with the result that they are dis-incentivised compared to other technologies. The issues are complex and are discussed in detail in the main paper.

Micro-CHP (below 2 kW) is, however, supported through feed-in tariffs (FiTs), with a cap restricting support to the first 30,000 units sold, and are thereby eligible for a generation tariff of 13.24p/kWh, plus a further 4.77p/kWh for power sold back to the supplier. This provides a clear incentive for the adoption of micro-CHP, regardless of the fuel or technology used, and represents an important enabler for fuel cell micro-CHP learning and early adoption. However, uptake has been slow and well below government’s expectations, probably due to a lack of established commercial products.

With regard to system benefits it is also clear that power produced by micro-CHP is generated disproportionately when power is expensive to produce and demand is high, as shown above. Current market arrangements reward micro-CHP generators on the basis of average power generation costs (avoided consumption) plus flat-rate FiTs, which have not been set to reflect the benefits arising from lower generation during peak times when it costs more (sometimes much more) to meet consumer demand. There therefore appears to be a case for reviewing current FiT arrangements to ensure that the additional system benefits are represented in price structures.

Further potential system benefits may arise from using surplus renewable electricity to produce hydrogen, and injecting it into gas distribution networks at concentrations below those requiring modifications to gas appliances. Power-to-gas projects of this kind could result in deferred or avoided electricity transmission grid upgrades, avoided or reduced needs for other forms of energy storage, as well as reduced curtailment of renewable power generation.

In terms of developing H2FC options for the future, government action is necessary to push these technologies forward in the near term in order for them to be able to play a significant role in coming decades. Although hydrogen and fuel cells have received public support from funders across the innovation landscape, there has been little systematic attempt to assess the priorities for hydrogen and fuel cells in heat. In addition to research, development and demonstration, support is likely to be required to facilitate the establishment of H2FC technologies in early markets—to build initial supply chains, establish cost reductions through scale economies, manufacturing innovation and learning-by-doing. Given the global nature of the emerging fuel cell
industry, the UK needs to evaluate where it can best participate and formulate policies to do so.

Other policy needs are the establishment of clear criteria relating to the environmental performance of hydrogen, particularly in respect of the carbon emissions deriving from its production; appropriate learning from policy support for deployment in other countries; and work on the full implications of converting gas networks to deliver hydrogen. The timescales of a cost-effective transition are sufficiently long that there is a case for embarking on that work now.

6. CONCLUSIONS

Commercial and industrial enterprises have used fuel cell CHP for decades, particularly in the USA. Fuel cell micro-CHP is rapidly becoming commercially available around the world, with the number of units doubling each year over the last decade. The capital costs of fuel cells have greatly reduced in recent years as a result of innovation and learning through field trials and commercial deployment programmes.

Hydrogen, which produces no CO₂ emissions at point of use, can replace natural gas for heating. Most technologies that use natural gas can be adapted to use hydrogen and will provide an identical or similar service, in contrast to other current low-carbon heating technologies such as heat pumps that are characterised by high capital costs, sensitivity to operating conditions and high space requirements for an average home. In the short term, injecting small amounts of hydrogen into the gas networks, or injecting synthetic natural gas produced from hydrogen and waste CO₂ effluent, could reduce the emissions intensity of the delivered gas. Such “power-to-gas” technologies would help to integrate renewables into the electricity system by avoiding curtailment of excess generation during low demand periods. In the longer term, the existing gas distribution networks and appliances could be converted to carry and use exclusively hydrogen. This process that might begin with R&D and field trials, followed by the incremental creation of more or less discrete ‘hydrogen communities’ using only hydrogen produced locally. These are important long-term options and keeping these options open requires government action now.

Most heat decarbonisation studies have considered neither hydrogen as a fuel for heating nor fuel cell CHP as a low-carbon heating technology. These studies reflect the habitual exclusion of hydrogen and fuel cells from innovation and technology assessments, and policy papers. Of the three studies that have considered hydrogen and fuel cells, two of them identify a cost-optimal role for hydrogen, powering fuel cell
micro-CHP in one case and hydrogen boilers in the other. Notably, only these two studies consider the economic benefits of converting the existing gas distribution networks to deliver hydrogen. The levelised costs of heat provision are reasonably close for a number of technologies. Particularly when non-economic characteristics are taken into account, none of the low-carbon technologies are clearly superior to the others and it is not clear that any one technology should be prioritised. An inclusive, portfolio approach to supporting new low-carbon technologies is appropriate for future heat provision.

Support for micro-CHP fuel cells is currently failing to provide the necessary bridge from the strong UK fuel cell R&D base into demonstration and on to full commercialisation, as indicated by the very low uptake of the micro-CHP feed-in tariff and the small number of UK demonstration projects in this area. This is partly because some government policies penalise hydrogen and fuel cell technologies compared to alternative low-carbon technologies; for example, some stakeholders noted that it is very difficult for fuel cells to qualify as “good quality” CHP under the current definition, yet proposed changes to the definition have not been implemented. There is a good case for adapting the current support system, perhaps with capital grants or a premium feed-in tariff for initial deployments of fuel cell micro-CHP. Most desirable would be the establishment of mechanisms that would reflect the value of CHP more generally for supporting peak electricity generation and avoiding network reinforcement, whether through a capacity-based incentive or through dynamic (or time-of-day) feed-in tariffs. These feed-in tariffs would not, unlike most feed-in tariffs, represent a subsidy, but rather a reflection of the value that they deliver to the wider electricity system. Government policies could also continue to promote innovation in this sector, linking the science base with existing commercial expertise in fuel cells, and aim to encourage the development of UK supply chains.

The UK has a strong scientific base in hydrogen and fuel cell research. A number of UK-owned and UK-based firms are international leaders in hydrogen and fuel cell technologies. The sector also includes globally-established suppliers of components as well as a number of innovative new entrants developing novel technologies and components. Support at home would enable UK companies to capture a share of fast-growing global supply chains for hydrogen and fuel cell heating technologies.
This White Paper has been commissioned by Hydrogen & Fuel Cell (H2FC) SUPERGEN to examine the roles and potential benefits of hydrogen and fuel cell technologies for heat provision in future low-carbon energy systems.

H2FC SUPERGEN 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. This paper is the first of four that will be published over the lifetime of the Hub, with the others examining: (i) low carbon energy systems (including balancing renewable intermittency); (ii) low carbon transport systems; and, (iii) the provision of secure and affordable energy supplies for the future.

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