INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2015) 1–10

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H2FC SUPERGEN: An overview of the Hydrogen and Fuel Cell research across the UK

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ARTICLE INFO

Article history:
Received 15 July 2014
Received in revised form
13 January 2015
Accepted 30 January 2015
Available online xxx

Keywords:
Hydrogen and Fuel Cell network
Academia-industry collaboration

ABSTRACT

The United Kingdom has a vast scientific base across the entire Hydrogen and Fuel Cell research landscape, with a world class academic community coupled with significant industrial activity from both UK-based Hydrogen and Fuel Cell companies and global companies with a strong presence within the country. The Hydrogen and Fuel Cell (H2FC) SUPERGEN Hub, funded by the Engineering and Physical Sciences Research Council (EPSRC), was established in 2012 as a five-year programme to bring the UK's H2FC research community together. Here we present the UK's current Hydrogen and Fuel Cell activities along with the role of the H2FC SUPERGEN Hub.

Introduction

The United Kingdom has a vast scientific base across the entire Hydrogen and Fuel Cell research landscape. It boasts a world class academic community coupled with significant industrial presence from a growing number of UK-owned firms alongside global companies with substantial UK presence in this area.

The Hydrogen and Fuel Cell (H2FC) SUPERGEN Hub was launched in May 2012 to bring together the UK's Hydrogen and Fuel Cell research community. Led by Professor Nigel Brandon (Imperial College, London) and funded by the Engineering and Physical Sciences Research Council (EPSRC), the Hub has an ethos of inclusiveness and openness to encourage collaboration, not only across the Hydrogen and Fuel Cell landscape, but also between academia, industry and government, linking fundamental research through to commercialisation.

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http://dx.doi.org/10.1016/j.ijhydene.2015.01.180

H2FC SUPERGEN has around 450 members working in Hydrogen and Fuel Cell technologies. The Hub's core structure comprises a Management Board of ten academics from seven UK universities. They are supported by an Advisory Board of representatives from around twenty key companies and government departments working in Hydrogen and Fuel Cell research and development. The Hub brings together the academic community through its Science Board of around 100-based UK academics working in the area. The Hub is free to join for anyone interested in Hydrogen and Fuel Cell activities, from within the UK and internationally.

H2FC SUPERGEN disseminates academic research funding, including funding for a series of White Papers aimed at informing policy makers and stakeholders about the role of Hydrogen and Fuel Cells across a number of areas, the first of which is now publically available [1] which details the role of Hydrogen and Fuel Cells in providing affordable, secure low-carbon heat.

The Hub works closely with EPSRC, the UK's public funding body for academic research, and holds workshops that are open to academics and key industry and government stakeholders to discuss the key priorities for funding. The Hub also supports international engagement and, for example, recently signed a Memorandum of Understanding (MoU) in the area of Hydrogen and Fuel Cells with the Republic of Korea. The Hub endeavours to expand our international collaboration further in the very near future.

The Hub strongly believes in collaboration between academia, industry and government. The UK has industrial activity across the entire Hydrogen and Fuel Cell supply chain and plays a pivotal role across SOFC (Solid Oxide Fuel Cell), PEFC (Polymer Electrolyte Fuel Cell) and AFC (Alkaline Fuel Cell) development, detailed below. The Hub's industrial Advisory Board seeks to encompass these key stakeholders and includes; Johnson Matthey, Rolls Royce Fuel Cell Systems, Ceres Power, Intelligent Energy, ITM-Power, Energy Technologies Institute, Ricardo plc, E4Tech, networks such as the Scottish Hydrogen and Fuel Cell Association, UK Energy Research Centre, and government departments and organisations including Department of Energy and Climate Change, Technology Strategy Board, EPSRC, Scottish Government and Scottish Enterprise.

Ceres Power specialises in SOFCs with a focus on fuel cell stack technology. In 2013 Ceres Power partnered with South Korea's largest boiler manufacturer, KD Navien, a major exporter of boilers to the USA, for initial development and product testing of a micro-CHP product for the Korean market. Edinburgh based Hydrogen and Fuel Cell firm, Logan Energy, delivers bespoke fuel cell CHP systems for clients across North America and Europe including the installation of 300 kW molten carbonate fuel cell powering The Crown Estate's £400 million 25 000 m2 Quadrant 3 scheme in central London [2]. As well as UK based companies, global companies are active in the UK. The Australian firm Ceramic Fuel Cells Limited (CFCL) launched its BlueGen SOFC micro-CHP unit with a scheme offering fully financed BlueGen units for social housing, schools and small businesses in the UK.

UK-based Intelligent Energy (IE) focuses on the development of PEFCs across the stationary power, automotive and consumer electronics sectors. IE led the *HyTEC* consortium to introduce a fleet of five zero emission fuel cell electric taxis that operate in London utilising a high efficiency PEFC and lithium battery powered electric hybrid with a 250-mile driving range, refuelled in less than 5 min at a publically accessible refuelling station at Heathrow Airport. The company also pioneered the first Hydrogen Fuel Cell motorbike and have developed fuel cell powered Upp mobile charger and are developing fuel cell back-up generators within the telecom sector in India.

UK company AFC-Energy is the world leader in Alkaline Fuel Cells and plays particular attention to stationary power markets has had considerable success in Korea and leads the FCH-JU funded project *Alkamonia* which looks at ammonia as a fuel source for alkaline fuel cells.

ITM-Power, based in Sheffield focuses on electrolysers and has launched a first Power-to-Gas (P2G) plant to the Thüga Group in Frankfurt, Germany [3]. They are the hydrogen fuel partner in *Hydrogen Island*, a project based on the Isle of Wight to demonstrate how a number of smart energy technologies to demonstrate how a future energy system can be configured.

Hydrogen production, distribution and storage are areas that have strong industrial support presence in the UK. Air Products are building a 49 MW waste gasification plant at Teesside in the North East of England, which can produce either electricity or hydrogen from waste.

Additional UK firms that are producing fuel cell products include Arcola Energy, Fuel Cell Systems, LightGreen Power and BOC. The UK has also recently seen new innovative start-up companies such as Ilika, Acal, Amalyst and Cella Energy.

There is strong and emerging interest in Hydrogen and Fuel Cells in the automotive sector. UKH2Mobility is a cross cutting industry –government programme consisting of three government departments and industrial representation from the global car manufacturing, infrastructure, utility and gas sectors. In 2013 UK H2Mobility released Phase I of their study where they explored the potential for Fuel Cell vehicles in the UK [4]. London has fuel cell buses which are part of the EU funded project, *CHiC* which operate the same way as any other bus in operation. A similar bus project has recently been launched in Aberdeen.

The UK industry is represented by both the UK Hydrogen and Fuel Cell Association and by the Scottish Hydrogen and Fuel Cell Association. Hydrogen London provides a platform for engagement with the Greater London Authority and has facilitated educational initiatives as well as project proposals and development.

At the Hub's core is a research programme that spans the whole Hydrogen and Fuel Cell landscape incorporating hydrogen production, storage, and systems, low temperature fuel cells (Polymer Electrolyte Fuel Cells (PEFCs)), high temperature fuel cells (Solid Oxide Fuel Cells (SOFCs)), policy and economics, safety, and education and training with each one of these research areas having an academic lead (see Fig. 1). An overview of some of the fundamental research is detailed in this article.

Fundamental research

Hydrogen systems

The main activity of the Systems group in the Hub involves the integration of different hydrogen and fuel cell systems and whole system modelling and optimisation.

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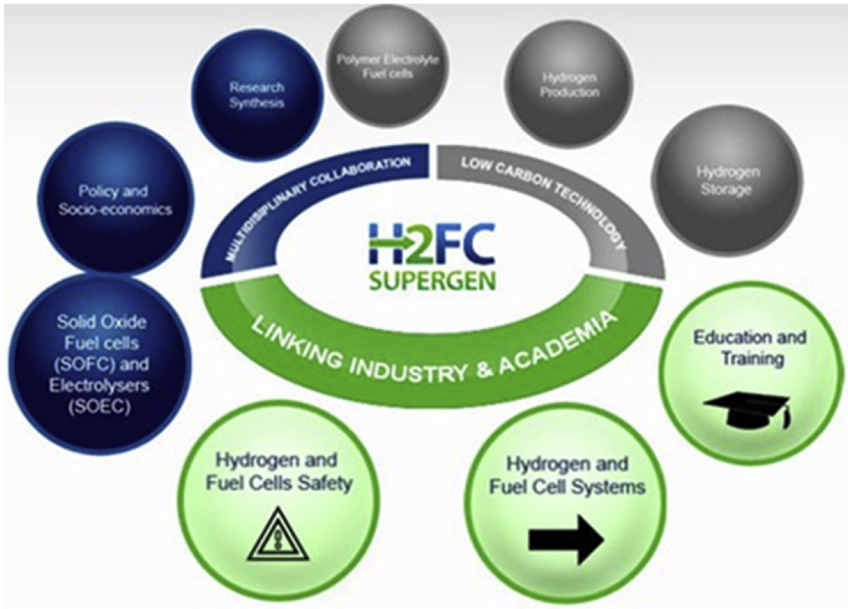

Fig. 1 – The research methodology within the Hub core programme consists of nine work packages and are led by the following academics: Professor Nigel Brandon, Imperial College (Director): Research Synthesis; Professor John Irvine, St Andrews, (Co-Director), SOFC/ECs; Professor Ian Metcalfe, Newcastle (Co-Director), Hydrogen Production; Dr Tim Mays, Bath (Co-Director), Hydrogen Storage; Professor David Book, University of Birmingham, Hydrogen Storage Materials/Education & Training; Professor Paul Ekins, UCL, Socio-economics and Policy; Professor Anthony Kucernak, Imperial College, (PEFCs); Professor Vladimir Molkov, Ulster, Hydrogen Safety; Professor Robert Steinberger-Wilckens, University of Birmingham, Education and Training; Professor Nilay Shah, Imperial College, Hydrogen Systems.

The widespread use of hydrogen as a future transport fuel requires the development of an appropriate vehicular refuelling supply chain. Similar to the existing petroleum supply system, the future hydrogen infrastructure should include production sites, storage facilities, delivery options, as well as conversion and end-use applications. In addition, there should be refuelling stations to support daily and seasonal fluctuations in demand.

A hydrogen supply chain, shown in Fig. 2, is a network of integrated facilities, or nodes, that are interconnected and work together in a specific way. The network begins with primary energy sources and terminates with fuelling stations.

Our Hydrogen Supply Chain (HSC) model [5–9] can be used to optimise the design and operation of the whole system over a long term planning horizon. The model includes spatial element (e.g. the region of interest such as the Great Britain divided into a number cells) and multiple time scales (e.g. decadal, seasonal, hourly).

The HSC model can be used to map out and analyse the H_2 network configuration given certain levels of penetration of fuel cell vehicles in the vehicular market. The example in Fig. 3 indicates that the existing petrochemical and petroleum plants will play a vital role in satisfying the hydrogen demand for transport. These existing plants are able to supply the whole GB hydrogen demand in 2015–2020. In 2039–2044, new facilities are needed to satisfy the large hydrogen demand.

Overall, the HSC model that is being developed by the Systems group in the H2FC SUPERGEN Hub can provide important insights on the development of the necessary infrastructure for producing, storing and distributing hydrogen to end-users.

Socio-economics

The Hub's socioeconomic research programme builds upon 10 years of UK hydrogen research from several institutions. This has focused primarily on the technological potential and the socio-economic challenges facing the large-scale deployment of hydrogen, and culminated in the first academic book on the socioeconomic challenges of hydrogen [10]. Much of this research has concentrated on the role of hydrogen-powered fuel cell vehicles in the UK, and globally, using energy system models. Highlights include the development of two UK spatial planning models for hydrogen delivery infrastructure [11,12], (See Fig. 4) an appraisal of the importance of technology learning for hydrogen vehicles in the global context [13], and research on innovation [14] and future scenarios [15], including using system dynamics modelling [16]. Recently, learning curves have been incorporated into the UK MARKAL energy systems model [17] and used to examine two high-profile publications by vehicle manufacturers (the Coalition and UK H2Mobility studies) [18].

Potential roles for Hydrogen and Fuel Cells in the wider energy system have received increasing attention in recent years. The potential for using the natural gas networks to deliver hydrogen has been assessed [19,20] and the Hub recently published a White Paper, aimed at policy makers, that examines the role of hydrogen in secure, low carbon

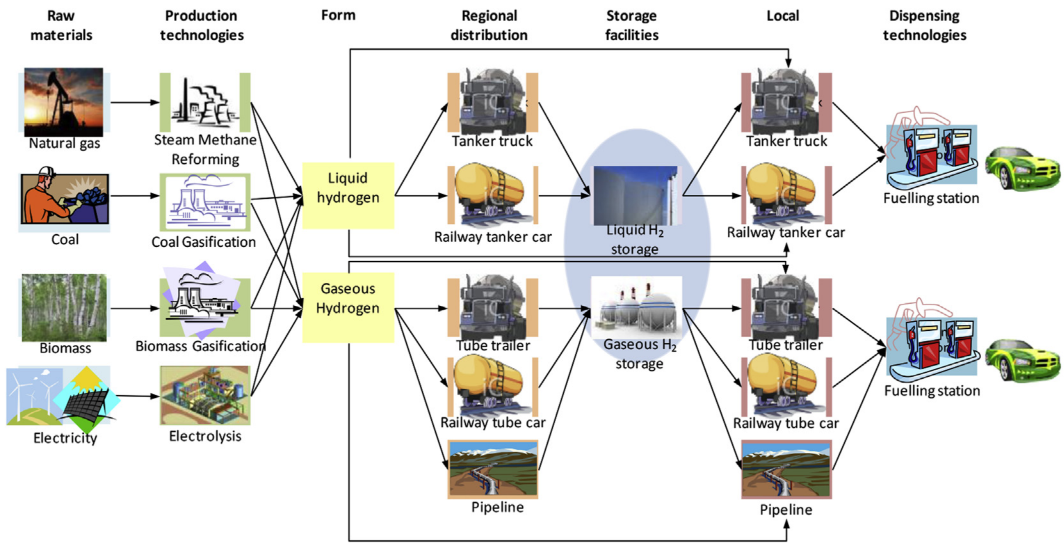

Fig. 2 – A hydrogen supply chain showing different technologies for producing, distributing, storing and dispensing hydrogen to the end users.

heating [1]. This paper shows that the cost of fuel cell CHP has reduced substantially through innovation in recent years to become cost-competitive with competing low-carbon technologies, while also avoiding some of the disadvantages of alternative technologies (see Fig. 5).

The Hub has developed a new energy system model, UKTM-UCL, which examines the potential benefits of inter-seasonal hydrogen storage within the whole UK energy system [21]. The new HYVE (Hydrogen's Value in the Energy System) project builds on this research. It is assessing the value of hydrogen for UK low-carbon electricity generation and gas systems, and for the transport and industry sectors, with the aim of identifying potential business cases for integrating hydrogen into different parts of the UK energy system in the future.

Hydrogen production

The global hydrogen production stands at around 448 billion m3 per year (40 billion kg per year) [22]. Hydrogen can be produced through several pathways. Within the UK, most of the hydrogen produced is from steam methane reforming (SMR). According to the UK H2Mobility report the hydrogen production mix that allows cost competitive hydrogen whilst delivering significant CO2 emission reductions should be predominately water electrolysis and SMR [4]. In this project we are investigating chemical looping hydrogen production that is used in SMR. Iron oxide is the typical oxygen carrier material (OCM) used to split water via chemical looping as several thermodynamically favourable oxidation states can be utilised [21–26]. In this process the OCM is repeatedly reduced by carbon monoxide and then re-oxidised by water to produce hydrogen. The product carbon dioxide and hydrogen are kept separate by the inherent design of the chemical looping system, which periodically exposes the OCM to the reducing or oxidising agent. When selecting a suitable OCM it is important to use a particle size that is not significantly greater than the effective diffusional length scale of oxygen within the material. This allows the whole capacity of the OCM to be utilised. In other words, an OCM that can maintain a small particle size, and thus a large surface area, is required. Iron oxide is therefore not ideal as its diffusional length scale of oxygen is believed to be quite short, and it suffers from thermal sintering at high temperatures (>800 °C). As a result it loses surface area while increasing particle size such that its activity decreases with cycling [27,28]. These problems could be overcome if the iron oxide (of sufficiently small particle size) were embedded in a stable matrix (one that does not, e.g., undergo a phase change) that has a long diffusional length scale for oxygen. This matrix material does not in itself require a high oxygen capacity but rather it provides a rapid oxygen transfer pathway to access a distributed reserve of oxygen in the iron oxide. We are employing the perovskite type material lanthanum strontium ferrite as the matrix component to encapsulate iron oxide particles of size 20–40 μm or smaller.

Hydrogen storage

The main focus of this element of the Hub's research is solid-state storage, including physical storage of molecular or di-hydrogen, H2, in nanoporous materials, such as activated carbons [29], and chemical storage, for example in complex hydrides such as magnesium borohydride, Mg(BH4)2 [30]. In addition to materials chemistry aspects, the Hub's storage research is also considered in a systems context (bridging production and end use of H2) and is linked to practical issues such as safety.

A key aim is to explore how solid-state systems compare with established technologies, mainly state-of-the-art compressed gas (70 MPa, 300 K), in particular to understand whether there are benefits in terms of increased capacity and/or less demanding operating conditions. The US Department

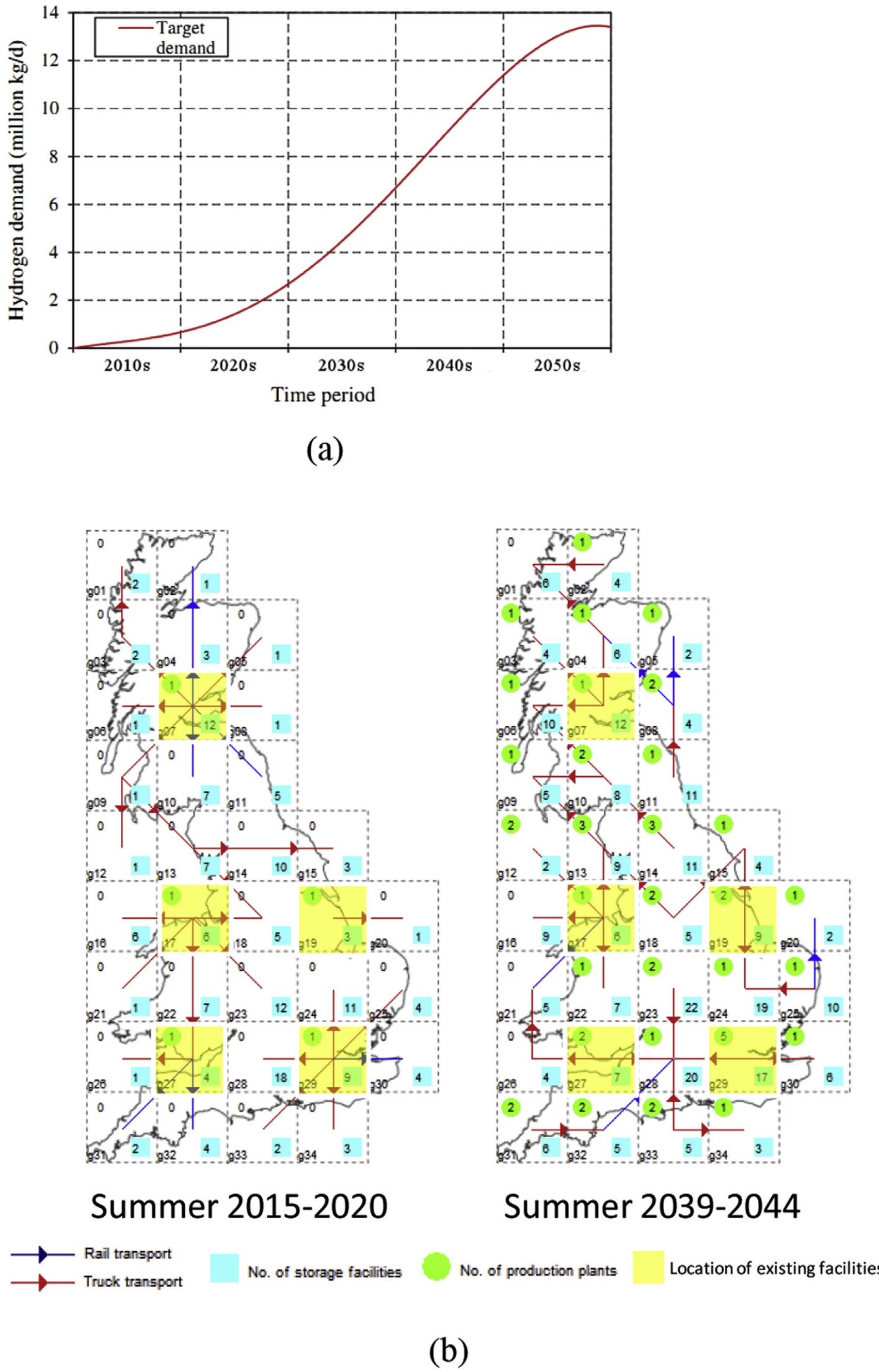

Fig. 3 – **(a) An example hydrogen demand trajectory for transport [6]; (b) optimal configuration of the H_2 network for the given target demand.**

of Energy (DoE) targets for onboard storage of hydrogen for light-duty vehicles [31] are useful performance benchmarks. For physical storage in nanoporous materials one of the main research challenges is to meet capacity targets (ultimately 2.5 kW h kg^{-1} and 2.3 kW h L^{-1} on a system basis) at temperatures approaching ambient. This problem is being addressed within the Hub by integrating capacious adsorbents into high-pressure Type IV storage tanks that may operate at close to 300 K, though may be charged cryogenically. As well as capacity, the research challenges with chemical storage are also concerned with aspects such the kinetics of the uptake and release of hydrogen. These kinetics for bulk materials

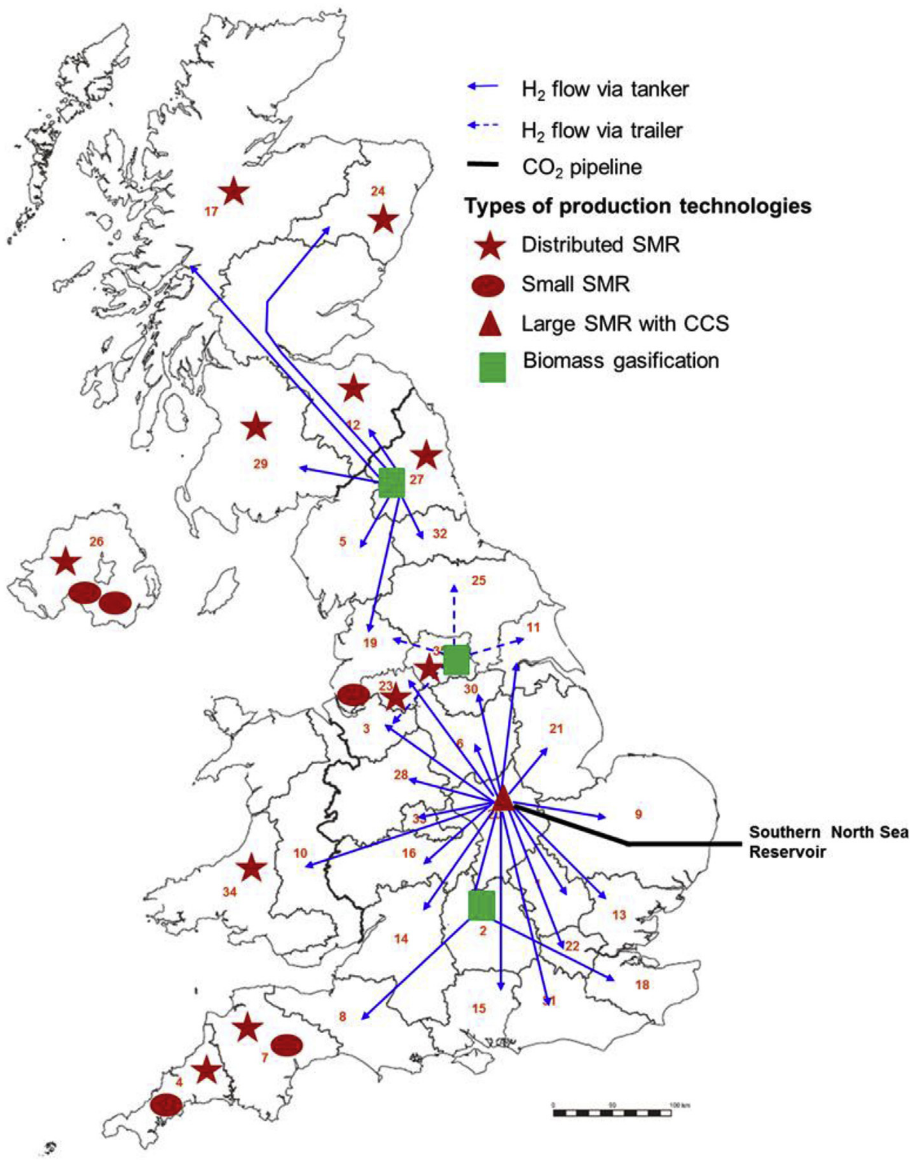

Fig. 4 – Spatial distribution of UK hydrogen production and delivery infrastructure in 2050 from the Spatial Hydrogen Infrastructure Model [12].

often require relatively high temperatures (typically >400 K) and may be slow. Materials developments are being made to address these problems (and to approach appropriate US DoE targets), for example by alloying, catalysis, and milling to lower temperatures and increase rates of dehydrogenation.

Hydrogen safety

Hydrogen safety research in H2FC SUPERGEN is aimed at studies of two main technical issues for inherently safer use of hydrogen systems and infrastructure. These are solutions for reduction of separation distances and the directly related problem of low fire resistance rating (FRR) of on-board storage. Testing of plane nozzles demonstrated that separation distances could be shortened by an order of magnitude if plane nozzles of thermally activated pressure relief device (TPRD) are used instead of a round nozzle of the same cross-section area. Numerical studies with plane nozzles reproduced the experimental data. The switch-of-axis phenomenon was reproduced showing that the longest axis of the plane jet in a far field beyond the shock structure is perpendicular to the longest axis of the plane nozzle [32]. This knowledge will be applied in design of innovative TPRD and their location to reduce deterministic separation distances and avoid impingement of hydrogen jet fire of a wheel assembly to comply with existing regulations.

An 'unexpected' result was obtained during comparison of a separation distance from an unignited release (size of flammable envelope, i.e. distance from the source to the lower flammability limit of 4% by volume of hydrogen in air) against

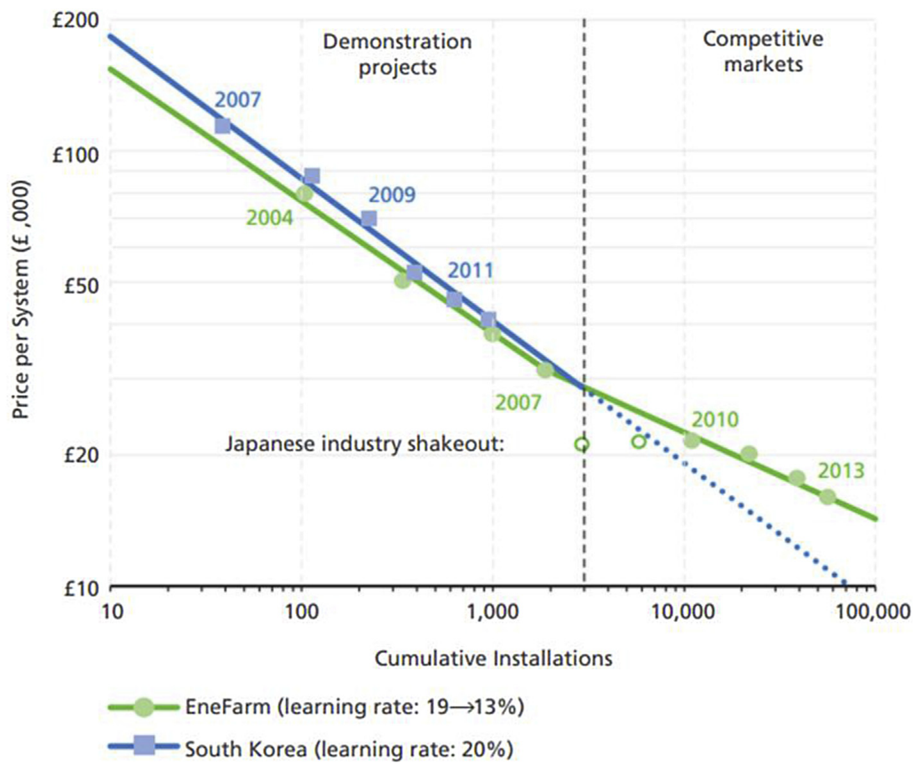

Fig. 5 – Fuel cell micro-CHP system cost reductions in Japan (EneFarm) and South Korea [1].

three separation distances from a jet fire from the same source of a leak [33]. While the 'third degree burns' distance is practically equal to the flammable envelope size, the 'pain' and 'no harm' distances are longer. This implies that separation distances have to be assessed for ignited releases (jet fires) rather than unignited leaks. This is valid unless separation from fireball, blast wave and missiles (including a vehicle itself) are longer. Reliable techniques for assessment of these separation distances have yet to be developed and validated to be used in the hydrogen safety engineering framework [34].

The preliminary study of FRR at Ulster has demonstrated the importance of standardisation of the bonfire fire heat release rate (HRR). Current regulations (GTR-2013) do not require a fixed HRR but require a temperature exceeding 590 °C at three points under the tank. This requirement can be achieved at different HRR. Numerical simulations demonstrated that the decrease of HRR from 350 to 75 kW results in the increase of FRR by more than an order of magnitude. Clearly, the GTR-13 bonfire test protocol has to be updated. Another result is the possibility to increase the FRR of the tank by using a resin with higher melting/glassing point.

These safety studies are contributing to the development of innovative safety strategies and engineering solutions within H2FC SUPERGEN.

PEFC

PEFCs are at a stage of maturity where commercial exploitation is starting. However, there is a complex interaction between cost, performance and longevity which still needs to be optimised. Crucial to achieving such an optimisation is improved understanding of the relationship between performance and degradation.

A number of degradation mechanisms known to operate within fuel cells are relatively poorly understood and parameterised. These degradation processes are: a) Corrosion of catalyst supports, microporous layers and GDLs during startup/shutdown and fuel starvation [35] [36]; b) Thinning of the electrolyte due to chemical degradation initiated by hydrogen peroxide and thermal effects [37]; c) Poisoning of catalysts by environmental contaminants (especially as the catalyst loading is decreased) [38].

Crucial to understanding and modelling these degradation issues is measurement of the underlying physical processes as a function of relevant operating conditions (temperature, pressure, humidity, reactant concentrations). Once these measurements have been made, material parameters may then be extracted (mass transport coefficients, diffusion coefficients, absorption constants, kinetic rate constants etc) which can be used to produce well parameterised models of fuel cell operation. These may be used to suggest approaches which negate the problem or to guide operation of PEFC systems away from "dangerous" operating conditions.

For example, one newly developed technique that has arisen out of research in this SUPERGEN project is a simple and precise ex-situ optical imaging method which allows imaging of reactant transport within fuel cell components. This approach is applied to measure oxygen concentration (as ozone) across the face of a pseudo fuel cell catalyst layer, with a serpentine design flow field [39]. This simple experimental technique is shown to be a powerful method in understanding

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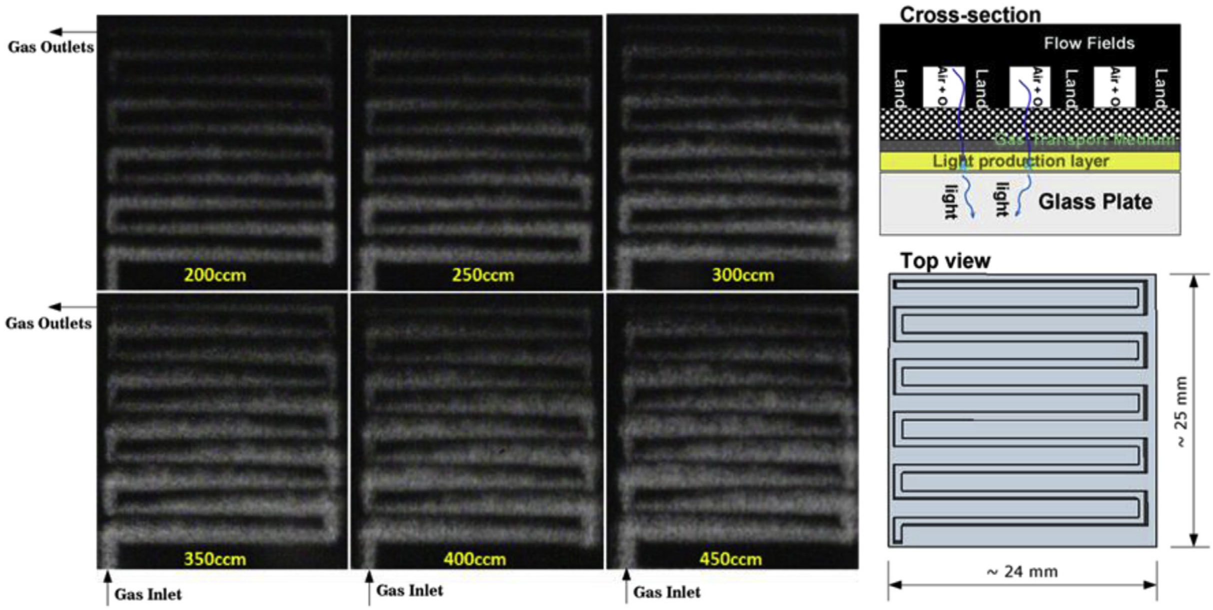

Fig. 6 – Oxygen concentration (as ozone) distribution through a flow field and gas transport layer (see right hand images for cross-section and plan-section of experiment). The six images on the left hand side show experimental images of light generation, highlighting those regions in which reactant permeation through the gas transport medium is enhanced. Secondary flow near flow field corners enhances light generation.

the performance of flow field, gas transport layer (gas diffusion layer) and microporous layers. This new approach allows direct imaging of flow under lands due to pressure gradients between the adjacent channels and non-laminar effects due to secondary flow around U-turns, Fig. 6.

SOFC/SOEC

SOFCs offer high electrical efficiency and are well suited to static power generation as they offer fuel flexibility and can run on fuels such natural gas, biogas, shale gas and coal gas as well as hydrogen. They offer high electrical efficiency even at the kWe scale and are ideal for combined heat and power operation due to the high quality of the heat produced. Solid Oxide Electrolysis Cells (SOECs) are closely related to SOFCs, and offer high efficiency hydrogen (and potentially syngas via CO_2 and steam electrolysis) production. Key challenges for SOFCs (and SOECs) relate to cost, durability, optimisation of interfaces, performance, and sustainability of materials. In this project, we focus on two critical issues; development and application of in-situ tools to understand durability, and new materials to alleviate concerns over materials supply.

Work is progressing on developing a novel rig for Raman measurements on operational single cells [40,41]. We also apply three dimensional characterisation and modelling of SOFC materials eg using X-ray tomography extending prior work to characterise the microstructure of a single phase LSCF cathode at 700 °C [42,43]. This approach is being extended to the widely used composite SOFC cathode materials, and the modelling framework previously developed to predict the electrochemical performance of Ni-cermets will be extended to these LSCF composite materials.

Concerns grow relating to future availability of the materials required to deliver a significant SOFC/SOEC infrastructure, eg limited availability of Rare Earth elements. SOFCs/SOECs use large amount of lanthanides, especially in the air electrode materials. Two approaches are considered for more sustainable and cheaper structures, firstly reducing lanthanide content and secondly replacing the air current collector (80% cathode vol) with Ln-free materials.

Education and training

The area of education in the Hub project is represented through the Centre for Doctoral Training (CDT) in ‘Fuel Cells and their Fuels’ at the University of Birmingham. CDTs are the main instrument through which the UK government supports PhD training. ‘Cohorts’ of ten to fifteen students per year are trained over an integrated four-year programme starting with one year of taught courses and mini-projects, followed by the usual three years of doctoral studies. The participation of the universities of Nottingham and Loughborough, Imperial College London, and University College London, as well as Ulster University and a variety of different schools across the universities gives the educational programme a highly interdisciplinary character.

Across the Hub and its associated PhD students are supported financially in taking part in the CDT modules offered at University of Birmingham by the five Hub partners and University of Ulster. The modules include basic and advanced courses on subjects related to H2FC technologies. These are organised as one week of intensive training, including tutorials and often also laboratory work. This activity allows students across the UK to attend specialised courses that will offer extra value in their PhD training.

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Through the Hub, an annual Researcher Conference is organised that gives students and researchers the possibility to display their work. This activity aims at further integrating the UK research activities in H2FC by especially targeting PhD students and young researchers. The second conference activity, the Fuel Cell and Hydrogen Technical Conference, is held annually in Birmingham. It brings together industry presentations and academic talks and serves as a basis for showcasing new research, discussing (inter)national FCH employment, and displaying current developments in industry. At a networking level, it supplies a platform for industry, academia, and also the funding bodies to interact.

The Joint European Summer School on Fuel Cell and Hydrogen Technology (JESS) is currently being organised by Research Centre Juelich, the Danish Technical University, and University of Birmingham. It builds on the EU project TrainHy run from 2010 to 2012. In the context of the CDT the modules of JESS are being coordinated to fit both the requirement of the UK CDT and the JESS so that specialised courses given by internationally leading researchers complement the taught part of the CDT training.

Conclusion

The UK has a very active academic and industrial research base in Hydrogen and Fuel Cells, from fundamental research to key players in industry. H2FC SUPERGEN endeavours to produce and facilitate world class fundamental research across the entire Hydrogen and Fuel Cell landscape and link through to the point of commercialisation. A collaborative approach between and within academia, industry and government is essential in bringing commercialisation of fuel cells and hydrogen into full fruition.

Acknowledgements

The authors would like to thank the Engineering and Physical Sciences Research Council for funding H2FC SUPERGEN (EP/J016454/1).

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Please cite this article in press as: Stockford C, et al., H2FC SUPERGEN: An overview of the Hydrogen and Fuel Cell research across the UK, International Journal of Hydrogen Energy (2015), http://dx.doi.org/10.1016/j.ijhydene.2015.01.180