The Role of Hydrogen and Fuel Cell Technologies in Low Carbon Energy Systems

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H2FC SUPERGEN

Who are we?

• H2FC SUPERGEN is an inclusive Hub funded by the RCUK energy programme, which reaches across
  – Academia
    • from Students to Senior Professors
  – Industry
    • from Researchers to CTOs
  – Government
    • Policy makers that have an interest in H&FC, etc

• It spans the whole H&FC technology landscape

• It is free to join:
  – www.h2fcsupergen.com
  – Dr Chloe Stockford c.stockford@imperial.ac.uk
Management Board:
10 Academics from seven UK universities, all leading a work package integrating a range of disciplines

Advisory Board:
A range of Industrial partners sit on our advisory board

Associate Membership:
Open to anyone working in H2FC research. The Hub has 240 Associate Members.

Science Board:
This Board comprises of around 80 UK-based academics working in H2FC research

Around 330 members of H2FC community
H2FC SUPERGEN
Our Core Research

Professor Nigel Brandon, Imperial (Director)
- Research Synthesis

Professor John Irvine, St Andrews, (Co-Director)
- Solid Oxide Fuel Cell/Electrolysers

Professor Ian Metcalfe, Newcastle (Co-Director)
- Hydrogen Production

Dr Tim Mays, Bath (Co-Director)
- Hydrogen Storage

Dr David Book, Birmingham:
- Hydrogen Storage Materials /Education & Training

Professor Paul Ekins, UCL
- Socio-economics and Policy

Professor Anthony Kucernak, Imperial College:
- PEM Fuel Cells

Professor Vladimir Molkov, Ulster
- Hydrogen Safety

Professor Robert Steinberger-Wilckens, Birmingham
- Education and Training

Professor Nilay Shah, Imperial College
- Hydrogen Systems
H2FC SUPERGEN Events

- UK-Korea H2FC meeting, Dec 2012, Birmingham
- Joint workshop with STFC on H2FC research, Feb 2013, Oxford
- Second Intl Symposium on SOFCs, April 2013, Imperial College
  - 11 national/international speakers with around 70 participants
- Support with EPSRC/TSB hydrogen Workshop, May 16th 2013
- Support with Carbon Trust/LCICG Hydrogen Workshop, June 2013
- H2FC Annual Conference alongside All-Energy, Aberdeen May 2013
  - 20 UK and overseas speakers. Good attendance and feedback
- Anion-Exchange Membrane Electrochemical Device Workshop, July 2013
- H2FC Researcher conference, 16th-18th December 2013
- H2FC SUPERGEN supported event with HFC NEC Conference March 2013
- Presence at external Conferences:
Introduction

• Energy in the UK.
• Why Hydrogen Fuel Cells for transport?
• Why NG Fuel cells for power and heat?
• Why Hydrogen for energy storage/system balancing?
• Conclusions.
The UK Energy Challenge

• One third of UK electrical generating capacity needs to be replaced in the next 20 years.
• The UK is seeking to reduce its CO$_2$ emissions by 80% by 2050 – it is expected that this will require complete decarbonisation of the electricity sector.
• In the April 2009 budget the UK Govt. committed to legally binding targets to reduce CO$_2$ emissions to 34% below 1990 targets by 2020.
• The UK has committed to EU targets to deliver 15% of its energy from renewable sources by 2020.
• The UK Climate Change Committee has just issued its fourth carbon budget and re-affirmed the need for the above.
UK: Share of fuels contributing to primary energy supply

- Heat: 39% UK CO₂
- Power: 33% UK CO₂
- Transport: 28% UK CO₂

89.8% fossil in 2010

Source: UK Energy Sector Indicators. 2011. DECC.
Final energy consumption by sector, 1980 to 2010

Source: UK Energy Sector Indicators. 2011. DECC.

(1) Services include the commercial sector, public administration and agriculture.
(2) Industry includes construction.
UK: Energy consumption by transport type

Source: UK Energy Sector Indicators. 2008. DECC.
Energy for transport

• 1 billion road transport vehicles today, 1.6 billion by 2030 (2012 BP energy outlook)
• Growth is mainly in non OECD countries (340 million to 840 million).
• Transport responsible for 23% of global energy related emissions (IEA world energy outlook 2008).
• Transport is the fastest growing sector for energy consumption in the UK, representing around 30% of our GHG emissions – UK transport GHG emissions are dominated by road (passenger cars 58%, vans 11%, HGVs 20% c.f. rail 1.9%).
Low Carbon Transport Options

• Reduce demand.
• Increase efficiency of current technology.
• Bio-derived fuels.
• Electric vehicles.
  • Hydrogen fuel cell electric vehicles.
  • Battery electric vehicles.
• Fuel cell-battery hybrid electric vehicles.
UK: Car use per person

Source: Driver and Vehicle Licensing Agency; Department for Transport; and Carbon pathways analysis July 2008.
Greenhouse gas savings of biofuels compared to diesel (well to tank)

Greenhouse gas savings of biofuels by feedstock and country of origin

N.B. provisional data

BG - bio gas
Ch - cheese by-product
Mol - molasses
msw - municipal solid waste
SB - sugar beet
SF - sunflower
Sul - sulphite
Unk - unknown

http://www.renewablefuelsagency.org/reportsandpublications/rtforeports.cfm
Biofuels

• Biofuels from waste products, and second generation biofuels from ligno-cellulose rich energy crops, do have the potential to make a positive environmental impact.

• The UK is very unlikely to achieve high levels of fuel security by growing bio-fuels on its own land, though we could make more use of waste.

• Sustainability in this area needs to be addressed at a global level as there is likely to be international trade in these commodities.

• Biofuels need to be combined with other developments, such as hybrid vehicles.

So why are hydrogen fuel cells of interest?

- A fuel cell is an energy conversion device - it converts fuel and air electrochemically into electricity (and heat).
- Fuel cells have the highest known efficiency of any energy conversion device – an efficiency which further increases at part load.
- By avoiding combustion fuel cells produce extremely low levels of NOx and particulates.
- Hydrogen can be produced from a variety of sources, providing security and flexibility.
Introduction to Fuel Cells

Membrane Electrode Assembly (MEA)/Positive - Electrolyte - Negative (PEN)

Fluid-Flow Plate (FFP)
Flow Channel

SOFC
Anode: \(2H_2 + 2O^2- \rightarrow 2H_2O + 4e^-\)
Cathode: \(O_2 + 4e^- \rightarrow 2O^2-\)

PEMFC
Anode: \(2H_2 \rightarrow 4H^+ + 4e^-\)
Cathode: \(4H^+ + O_2 + 4e^- \rightarrow 2H_2O\)

Solid Oxide Fuel Cell
Proton Exchange Membrane Fuel Cell
Why do we need Fuel Cell and Battery EVs?

Fuel cell - battery electric vehicles

<table>
<thead>
<tr>
<th></th>
<th>Petrol</th>
<th>Hydrogen</th>
<th>Electricity (2008)</th>
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<tbody>
<tr>
<td>CO₂ emissions / gCO₂ MJ⁻¹</td>
<td>77.6</td>
<td>76.9</td>
<td>150</td>
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<tr>
<td>Fuel consumption / MJ mile⁻¹</td>
<td>2.93</td>
<td>1.46</td>
<td>0.73</td>
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<tr>
<td>Emissions / gCO₂ mile⁻¹</td>
<td>227</td>
<td>112</td>
<td>110</td>
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<tr>
<td>Emissions / gCO₂ km⁻¹</td>
<td>142</td>
<td>70</td>
<td>68</td>
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Routes to Hydrogen Production

- Nuclear Energy
- Non-Fossil Energy (Solar, Water, Wind)
- Fossil Energy

- Heat
- Mechanical Energy
- Electricity
- Thermolysis
- Electrolysis

- Photoelectrolysis

- Biomass
- Biophotolysis
- Fermentation

- Chemical Conversion

- Hydrogen
- Carbon dioxide

Final Energy Consumption of Thermal Energy in the UK in 2006

Space heating and hot water in UK residential sector = 78Mt CO₂ pa. In 2008

UK: Domestic energy consumption

Source: Derived from BREHOMES. taken from the Domestic Energy Fact File.
Building Research Establishment
Fuel Cell Boilers for the Home (micro-CHP)

**Conventional**
- Fuel
  - Energy 100%
  - Power station 55% losses
- Transmission 5% losses
- Delivered 40%

**Micro-CHP**
- Fuel Cell
  - Energy 100%
  - Fuel Cell 10% losses
  - Electrical 40%
  - Heat 50%
- Delivered 90%
Micro-CHP Technologies

- Vaillant and Plug Power PEMFC
- Honda ECOWILL ICE
- Baxi Stirling engine
- Honda ECOWILL ICE with Storage
- Ceres Power and British Gas SOFC
SOFC mCHP electrical efficiency against load factor

\[ \text{eff} = 0.04911 \times r^3 + 0.007991 \times r^2 - 0.2849 \times r + 0.5924 \]

Residential heat and power demand

Heat and Power Demand over 1 Day in a Typical UK Dwelling
The main value driver for micro-CHP is (the ability to displace) onsite electricity demand.

If onsite electricity demand exists, the ability to access the value available (in displacing it) is dependent on the heat-to-power ratio (HPR) and presence of thermal demand.

Environmental Drivers for m-CHP Systems

CO₂ Reduction – Thermal Demand

- CO₂ reduction is dependent on ability to displace grid electricity.
- Ability to displace grid electricity, and thus bring about CO₂ reduction, is dependent on annual thermal demand and prime mover heat-to-power ratio.

1kWe SOFC Micro-CHP System in a Residential Dwelling

Current Break-Even Point for SOFC-based Micro-CHP
Possible Future Break-Even Point for SOFC-based Micro-CHP if Gas CO2 Rate is Halved

DEFRA long term CO2 Rate for UK Electricity
Gas CO2 Rate = 0kg/kWh
Gas CO2 Rate = 0.04kg/kWh
Gas CO2 Rate = 0.09kg/kWh
Gas CO2 Rate = 0.14kg/kWh
Gas CO2 Rate = 0.19kg/kWh

marginal CO2 intensity of UK electricity 0.69kgCO2/kWh

Annual CO2 Reduction (kgCO2/year) compared with conventional grid/boiler energy provision

Electricity CO2 Rate (and Credit Rate for Micro-CHP Generated Electricity) (kgCO2/kWh)
The need for energy storage

• A whole systems analysis of the benefits that storage brings to the energy system against a range of future low carbon energy scenarios has been undertaken. This approach reveals trade-offs between different services, which storage can provide.

• Storage technologies are represented through generic properties, such as round trip efficiency, storage duration (the ratio of energy and power capacity), geographical location and voltage level on the network it connects to (also referred to as bulk or distributed storage). Hydrogen production offers one such storage option.

• A full report* on the study can be found at www.carbontrust.com/media/129310/energy-storage-systems-role-value-strategic-assessment.pdf

Selected Highlights

• The optimal location for bulk storage in the UK is in Scotland, where it supports the integration of wind and avoids additional transmission reinforcement with northern England. Distributed storage is predominantly located on networks in high demand regions in Southern GB, especially in conjunction with a high uptake of electrified transport and heating.

• The value of storage in the UK increases markedly towards 2030 and further towards 2050. Carbon constraints for 2030 and 2050 can be met at reduced costs when storage is available. For bulk storage cost of £50 per kW per year, the optimal volume deployed grows from 2 GW in 2020 to 25 GW in 2050. The equivalent system savings can reach over £10bn per year in 2050.
Power to Gas

- Refers to the generation of hydrogen using fast response electrolysis and its storage and/or injection into the gas network for heat and power.

- Can also include the generation of hydrogen for combination with CO$_2$ in chemical or biological methanation reactions, and injection of the produced methane into the gas grid.

- Green hydrogen in the *gridgas* study is defined as 50 g CO$_2$/kWh (cf. 190 g CO$_2$/kWh for natural gas), and up to 3 vol% H$_2$ by volume could be injected into existing gas networks, though current regulations restrict this to 0.1 vol%.

*Power to Gas: a UK feasibility study; (2013) www.gridgas.co.uk
The value of storage is not strongly affected by increases in storage duration beyond 6 hours (shown here is a 10 GW case in base case scenario in 2030, Strbac et al for Carbon Trust). Distributed storage initially gains more from an increase in energy at a given power than bulk storage.

Low cost solutions are needed in both cases as energy requirements increase.

Hydrogen production through electrolysis could have an important role to play as energy requirements increase.
Importance of round trip efficiency

Round trip efficiency does not have as significant impact an impact on the value of storage as might be expected, but an increase in efficiency does open up a larger market as more storage is deployed (shown here is the 2030 base case with 24 hour capacity). It is therefore important to consider the overall costs, scaleability, and lifetime of storage – round trip efficiency alone is not a good selection criteria.

The Future of Hydrogen and Fuel Cells in Low Carbon Energy Systems

• Hydrogen fuel cell electric vehicles are one of the few routes to enabling low carbon transport. While hydrogen from natural gas makes carbon sense today, future work must focus on low carbon routes to hydrogen, e.g. from CCS or electrolysis with nuclear/renewables.

• High efficiency power and heat generation using fuel cells operating on natural gas is an important technology today as gas use grows. But in the longer term attention must be paid to the carbon content of gas, e.g. using blended hydrogen, or bio-gas, or synthetic methane.

• Hydrogen generation using electrolysis offers flexibility/storage in future low carbon energy systems. This flexibility will have increasing value in the future as we combine e.g. intermittent renewables with inflexible nuclear.

• We are now seeing the commercial uptake of these technologies.
Thank you

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www.imperial.ac.uk/energyfutureslab
Sensitivity of annualised cost to technology risk and lifetime

\[ A = C \times \frac{WACC}{1-(1+WACC)^{-n}} \]

<table>
<thead>
<tr>
<th>Storage asset</th>
<th>Economic life (years)</th>
<th>Real WACC</th>
<th>Capital cost (£/kW)</th>
<th>Annualised cost (£/kW/yr)</th>
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<tr>
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<td>10</td>
<td>14.5%</td>
<td>256</td>
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2030 Distributed storage