Delivery of Sustainable Hydrogen

John Irvine

UK EPSRC Supergen Consortium XIV
1st October 2008 - 2012
Hydrogen Production

- Nuclear Energy
  - Heat
    - Mechanical Energy
      - Thermolysis
      - Electrolysis
      - Photolysis
      - Hydrogen
      - CO₂
    - Electricity
  - Photo-electrolysis

- Renewable Energy
  - Photo-electrolysis
  - Hydrogen

- Fossil Energy
  - Biomass
    - Conversion
    - Hydrogen
    - CO₂
Mission

• The hydrogen economy needs large volumes of hydrogen produced with much lower carbon footprint.
• We address a significant gap in the EPSRC portfolio, as production of sustainable hydrogen is largely absent.
• We seek to convert electrons, hydrocarbons and biomass-derived fuel sources into hydrogen or indirect hydrogen carriers.
• We focus on lower cost and improved efficiency catalytic and electrocatalytic processes and their socio-technical impacts.
• Complementarity of the different processes based on what might be termed multi-chemistry approaches.
Delivery of Sustainable Hydrogen

13 Universities £5M 71 man-years
6 PhD Students and 500 researcher months

University of St Andrews, John TS Irvine
Newcastle University, Ian S Metcalfe
University of Manchester, JC Whitehead
Cambridge University, Bartek Glowacki,
Strathclyde University, David Infield
Andrew Cruden
University of Birmingham, David Booth
University of Warwick, Martin Wills

Imperial College, Kang Li
Marcello Contestabile.
Heriot-Watt University, Shanwen Tao
Cardiff University, Neil B. McKeown
Oxford Chemistry, Edman Tsang
Brunel University, Malcolm Eames
Leeds University, Valerie Dupont
<table>
<thead>
<tr>
<th>Industrial Involvement</th>
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<tbody>
<tr>
<td>Carbon-&gt; Hydrogen</td>
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<td>Johnson Matthey, GKSS DSTL</td>
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<td>Electrons -&gt; Hydrogen</td>
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<tr>
<td>Ravensrodd, Valeswood, Bryte Energy</td>
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<td>Demonstration</td>
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<td>PURE The Hydrogen Office</td>
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<td>KT</td>
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<tr>
<td>Scottish Enterprise, SHFCA, UKHA, The Centre for Process Innovation, IChemE</td>
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WP1

$\text{H}_2$ from carbonaceous sources

Ian Metcalfe
Combined reaction and separation using:
- Membranes
- Periodic reactor operation

The chemistry and materials are the same/similar
Reaction pathways – low temperature

Advanced hydrogen production processes

\[ \text{HCO} \xrightarrow{\text{H}_2\text{O}} \text{H}_2\text{O} \xrightarrow{\text{H}_2\text{O}} \text{CO} \xrightarrow{\text{H}_2\text{O}} \text{CH}_4 \]

\[ \text{CO}_2 \xrightarrow{\text{H}_2\text{O}} \text{H}_2 \]

Selective WGS catalysts

\[ \text{CO}_2 \text{ sorption/membranes/utilisation} \]
Reaction pathways – high temperature

Membrane reaction, air separation, membranes, periodic operation

HCO

H₂O, O₂

CO
H₂

H₂O

CO₂
H₂

CH₄

CO₂ sorbtion to shift WGS equilibrium

Membrane separation, periodic operation
1.1 Advanced hydrogen production processes (Leeds, Manchester, Warwick, Oxford, Newcastle)

Hydrocarbon and oxygenated hydrocarbon reforming through

- Nanostructured catalysts (low temp selective WGS)
- Organometallic catalysts (Selective $H_2 + CO_2$)
- Plasma catalysis (Poor selectivity – need WGS cat)
1.2 Membranes and membrane processes (Newcastle, Imperial, Cardiff, Birmingham with St Andrews, Heriot Watt)

- Organic membranes (polymers of intrinsic microporosity for CO$_2$ separation from H$_2$)
- Metallic membranes (new Pd alloy membranes)
- Ceramic membranes (mixed conducting – oxygen ion and electron and proton and electron – membranes)
1.3 Integrated processes (Newcastle, Imperial, Cardiff, Birmingham, Leeds, Manchester, Warwick, Oxford)

- Membrane and membrane combination
- Integration of plasma-activated processes with ion-conducting membranes
- Periodic reactor operation
- Carbon dioxide utilisation
Hydrogen production from water vapour with plasma

\[ \text{H}_2 \text{O} \rightarrow \text{CO} + \text{CO}_2 + \text{H}_2 \]
Chemical looping with in-situ CO₂ sorption

Mechanism illustration for fixed bed reactor

\[ \text{Ni} + \text{MCO}_3 \rightarrow \text{NiO} + \text{MCO}_3 \]

\[ \text{NiO} \rightarrow \text{Ni} \]

\[ \text{HC} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 \]

\[ \text{NiO} \rightarrow \text{MO} \rightarrow \text{MCO}_3 \]

\[ \text{O}_2, \text{CO}_2 \]

\[ \text{H}_2, \text{H}_2\text{O}, \text{trace CO}_2, \text{CO}, \text{CH}_4 \]

New materials, e.g., perovskite OTMs
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WP2

H₂ from electrons

John Irvine
2.1 Optimisation and Development of Electrolyser Systems

- Alkaline electrolysers
- Optimise for cost and variable output operation
- Modelling and laboratory testing of highly distributed H₂ generation system
2.2 High Temperature Electrolysis

H2 → H2O + O2

Cathode | Electrolyte | Anode

H2O → H2 + O2

Cathode | Electrolyte | Anode

Solid oxide fuel cell

Solid oxide electrolysis

ΔH (total energy demand)

ΔG (electrical energy demand)

H2O liquid

TΔS (heat demand)

Temperature T/°C

Spec. Energy E/kWh/Nm3H2

1

2

3
# 2.3 Ammonia Production

<table>
<thead>
<tr>
<th>Measure</th>
<th>Production Method</th>
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<tbody>
<tr>
<td></td>
<td>Natural Gas</td>
<td>Electrolyzer + H-B</td>
<td>SSAS</td>
</tr>
<tr>
<td>Energy required per ton of NH₃</td>
<td>33 MBtu = 9700 kWh</td>
<td>~12,000 kWh (H₂ production only)</td>
<td>7000-8000 kWh</td>
</tr>
<tr>
<td>Capital cost per ton/day NH₃ capacity</td>
<td>~$500,000</td>
<td>~$750,000 (Cost dominated by electrolyzer)</td>
<td>&lt;$200,000</td>
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<tr>
<td>“Fuel” cost to produce 1 ton of NH₃ at large scale [1]</td>
<td>Depends on location and NG cost</td>
<td>$420 (3.5 ¢/kWh)</td>
<td>$245 (3.5 ¢/kWh)</td>
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<td></td>
<td></td>
<td>$240 (2 ¢/kWh)</td>
<td>$140 (2 ¢/kWh)</td>
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<tr>
<td>Cost of 1 ton NH₃ at moderate to large scale [2]</td>
<td>Depends on location and NG cost</td>
<td>&gt;$600 (3.5 ¢/kWh)</td>
<td>&gt;$315 (3.5 ¢/kWh)</td>
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<td>&gt;$400 (2 ¢/kWh)</td>
<td>&gt;$210 (2 ¢/kWh)</td>
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<tr>
<td>Tons of CO₂ emitted per ton of NH₃ produced</td>
<td>1.8</td>
<td>-0-</td>
<td>-0-</td>
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LANL
The energy requirement for hydrogen liquefaction is high: typically 30% of the calorific value of hydrogen; new approaches that can lower these energy requirements and thus the cost of liquefaction are needed. Here, we seek to develop new concepts that exploit the characteristics of high pressure electrolysis to address this:

a) oxygen-hydrogen thermo-acoustic compressor

b) Liquefaction of the hydrogen using products of high pressure electrolysis (O₂ and H₂)
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WP3
Socio-Technical Analysis & Appraisal of Hydrogen Production
Malcolm Eames
Hydrogen SUPERGEN: WP3

WP3  Socio-Technical Analysis & Appraisal of Hydrogen Production (Brunel, ICEPT, St Andrews & Newcastle)

- Interdisciplinary WP integrating engineering & socio-economic knowledge and expertise
- Will illuminate both the technological & economic potential and environmental & social impacts of the prospective technologies being developed by the consortia
- Quantitative and qualitative analysis: infrastructure and demand modelling, multi-criteria, participatory and deliberative methods
- Distinctive and complementary to existing UKSHEC & UKERC research portfolio
WP3 Sub Tasks

- 3.1 Benchmarking (St Andrews & Newcastle, ICEPT & Brunel)
- 3.2 Characterisation of prospective technologies (Brunel & ICEPT)
- 3.3 Techno-economic analysis (ICEPT)
- 3.4 Participatory technology assessment of novel H2 production technologies (Brunel)
- 3.5 Recommendations for policy and industry (Brunel & ICEPT)
4.2 Innovation systems and socio-technological transitions (Brunel)

- International comparative analysis of hydrogen innovation systems (UK, Germany, Japan, Korea, US & Canada)
- Technology Specific Innovation Systems (TSIS) functional approach (entrepreneurial activities, knowledge development, networks, guidance of search, market formation, etc) will provide:
  - Insights for policy regarding promotion of low Carbon economy
  - Empirically and theoretically grounded evidence-base to underpin innovation, KT and rapid commercialisation of hydrogen technologies
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WP4 Management, Networking, Training and Knowledge Transfer

John Irvine,
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<th>Knowledge Transfer</th>
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<tr>
<td>• Advisory Group/Panel</td>
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<tr>
<td>• Open Meetings</td>
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<tr>
<td>• Dissemination</td>
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<tr>
<td>• Project Manager</td>
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<tr>
<td>• Specialist Consultancy Support</td>
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Outreach

- International linkages
  - China, South Africa, Denmark, Canada, …
- Training schools
- Open meetings/workshops
- Advisory Group
- Project Manager
Summary

- Clear technical focus – Intensified Hydrogen Production Processes
- Genuine interdisciplinary research focus
- Socio-economics research facilitating emergence and development of prospective technologies
- Changing the economics of distributed Hydrogen Production