Hydrogen and Fuel Cells Workshop 23 February 2012 – Outputs

The workshop produced a great deal of detail and it is clear that this research theme has a great many research challenges. The outputs of the workshop were grouped into broad headings, the detail is listed in the Annex at the end of this document.

I have grouped the outputs into three broad theme headings, under which I have grouped sub themes. These are:

SYSTEMS

- Whole fuel cell systems
- Systems integration
- Safety
- Socio-economics and policy
- Durability/Reliability
- Applications

FUELS

- Production of fuels
- Distribution and infrastructure
- Storage

UNDERPINNING

- People issues.
- Materials

Please bear in mind that these broad theme and sub theme headings are only intended to help order the outputs of the workshop. There is a great deal of cross over between the sub themes, and this should be remembered when thinking about the challenges.

The other issue that needs clarification is the definition of whole fuel cell systems and sub systems. For whole fuel cell systems the reader should think in terms of the whole social, policy, economic, technological and environmental system. Within the whole system theme sits the sub systems theme, and indeed there are sub systems within sub systems.

Some issues that were raised at the workshop were cross cutting or underpinning. These were mostly people issues, as in training or the supply of qualified/experienced people, and Materials research. Also mentioned were manufacturing issues. Whilst not directly energy research they identify a crucial aspect of developing hydrogen and fuel cells energy systems as a competitive technology as well as supporting the development of the hydrogen and fuel cells Industry in the UK.

SYSTEMS

Whole fuel cell systems

There was a wealth of detail provided at the workshop underpinning the issues around fuel cells as whole systems. It is clear that this theme presents a rich area for research, although, due to the scale of the whole system it is unlikely that a single programme of research would be able to address everything. As a theme it could be said that it includes all the other sub themes. Thus when reading the annex list of challenges the reader will find it broken down into sub themes; how various systems are integrated into a whole; understanding the economics and life cycle; safety and environmental impacts, application and integration into existing power distribution system; etc..

The subdivision is not intended to guide the reader to think in terms of breaking the whole systems challenges into discrete parts, rather it is intended to highlight the diversity of the challenges. A 'grand' challenge would be to bring a number of these subthemes together into a coherent research agenda with a clear goal. It is intended that the SUPERGEN Hydrogen and Fuel Cells Hub will begin to pull the various research projects together in a whole systems approach.

Systems integration

Systems integration research is about how to bring together sub-systems to produce a larger functioning system. The detail given in this section should be considered alongside that in the whole systems section. There are a number of specific challenges highlighted in the annex, from dynamic system modelling and systems control to thermal management and heat storage.

Safety

Safety is a issue that is going to have to be addressed before there will be any large scale roll out of this technology, mostly around dealing with hydrogen (given that other hydrogen carriers such as methane are already widely used and have existing safety protocols). The short list of safety issues described in the annex give a flavour of the known issues,the challenges relate to the studies needed to enable the regulators to enact the necessary legal regulation that will give insurers and users confidence that the technologies are safe.

Socio-economics and policy

This is another area where there is much detail in what needs to be done to make the technology acceptable, from public acceptance to market acceptance, and in how the transition from the current energy system to any new system may be managed.

Durability/Reliability

Again this was another area that produced a great deal of detail on the challenges. It includes areas as diverse as diagnostic and in-situ techniques, materials stability (see also materials section), the effects of contamination, and systems integrity.

Applications

How the fuel cell or hydrogen fuel is to be used strongly influences the challenge that it will face as a useable technology. Small mobile applications of fuel cells such as hand held electronics will have different challenges from large static applications. Whilst applications are not a research area they do provide context for other research areas such as systems integration, storage systems etc.

FUELS

Fuels for Fuel Cells

A range of hydrogen carriers are relevant to this sector, ranging from hydrogen, through to methane to renewable fuels such as alcohols and bio-gas. The relationship between the fuel cell application, the fuels that could be used and the wider energy system were also seen as important and should not be forgotten. Also identified were general issues around flexible fuel processors, and the ability of cells to tolerate fuels from different sources, and impure fuels.

Production of fuels

Detail in this section was mostly around the production of hydrogen from various sources and the subsequent purification of the hydrogen. There was some discussion around understanding different electrolysis methods and how high efficiency electrolysis is a key research challenge.

The feedstock used as a source of the hydrogen was seen as being very important, as the routes to hydrogen generation should be low carbon, either through electrolysis using renewably generated electricity or producing hydrogen from biological sources.

Direct conversion of solar energy into hydrogen was seen as a key research area that is receiving increased attention globally. Also highlighted was the research needed in membranes, catalysts and electrolysers all of which are directly relevant technologies.

Distribution and infrastructure

This is linked to the broader issue of hydrogen and fuel cell systems, how to integrate production, delivery and use of hydrogen more efficiently. Also, how can the system be made robust and integrated with current fuel distribution systems.

Storage

Storage of fuels, especially of hydrogen, is a widely researched area and there was a good level of detail produced at the workshop as would be expected. Many issues were highlighted. There was discussion around the different infrastructure requirements for different storage methods, ranging from small scale portable devices to larger scale compressed gas and bulk liquid as well as solid state storage. Each type has its specific research challenges. There was also a discussion around novel liquid carriers (synthetic fuels) as well as more conventional liquid fuels such as ammonia, methane and formic acid.

At the extreme end of the scale was discussion of geological storage of hydrogen in a similar manner to the underground storage of natural gas.

Other areas that were highlighted were hybridised storage systems, and closed systems for on-board reforming. Storage was strongly cross referenced to safety and how such facilities would work in the real world.

UNDERPINNING RESEARCH

People issues.
There was a consensus that there is a growing demand for trained and experienced people in the hydrogen and fuel cells industries. It was noted that the CDTs need to be flexible in allowing a breadth of hydrogen and fuel cells research to be covered. The need for fellowships were also highlighted in the post doctoral and early career stages.

Materials
It was noted that there are materials research issues right across the range of different hydrogen and fuel cell technologies. The list of materials research challenges in the annex is comprehensive but not exhaustive.

Main conclusions drawn from the workshop for the call remit

The workshop produced considerable output, describing the research issues quite thoroughly. There is already research being done in this sector and any challenge application should refer to what is being done both in academia and industry and make a clear identification of the gap in the research landscape that the challenge is filling.

The themes that came out as being most critical were:

Social and economic
The economic case for hydrogen and fuel cells as a viable technology needs to be clearly made. Also, how the public will react to this technology in its various applications needs to be clearly understood if it is to be widely adopted. Therefore, understanding how the economics/market/technology/social aspects interact and being able to communicate this clearly to policy makers in order to enable evidence based policy decisions to be made is essential. This theme incorporates safety, policy, public acceptance, market acceptance, transition understanding, economics and environmental impact. **Any proposal in this theme would have to be multidisciplinary and incorporate most if not all of the above areas.**

Sub system level research
As this theme is the one that is highly relevant to the research community it is likely to attract significant interest. This is a broad and diverse theme, with many different sub-systems level research issues (highlighted in the Annex). The theme includes research into discrete parts of larger systems and can mean anything from part of a fuel cell unit to a hydrogen distribution network. This theme incorporates the underpinning research that will develop technology that will enable implementation of hydrogen and fuel cells as a viable energy vector.

Any submission in this area should be looking at a sufficiently complex sub-system that the research is multidisciplinary. Submissions should show that the applicants are aware of what research is already being done in this area and articulate where the research gap is, and why it is important that the gap is addressed, and define how the proposed research will move the technology as a whole forward.

Please note that for potential applications that deal predominantly with materials research it would be more appropriate for them to be submitted as a standard mode application (responsive mode) in the Physical Sciences programme. Please see the Physical Sciences page of the EPSRC website for details of the Materials for energy initiates.

Systems integration

Bringing the various sub-systems together is also critical to producing a competitive power delivery system. Understanding how to bring the various sub systems together to maximize the system efficiency is also needed for the economic case outlined in the socio-economic theme described above. There are many levels of systems integration; for example, the integration of fuel cell modules into the power distribution network, or the integration of fuel cell components into a module. The annex should be referred to for a comprehensive list of issues. Again, any applicant in this area should demonstrate that the proposed research is filling a gap in the research landscape and making a clear case as to the importance of the research.

Annex

Challenges as identified at the scoping workshop

SYSTEMS

Whole Systems Analysis

Systems Integration

- Heat/power integration into built environment
- Integration of static & transport
- Resilient energy system
- Intersection with future energy systems
- H_2 needs to link into wider transition to low carbon vehicles
- Understanding dynamic response & impact
- What are the benefits of having FC without H_2 compared to other options?
- Low cost, variable, intermittent (low capacity factor), smart
- Electrolysis for smart grids

Socio economics

- FCV v. EV v. H.ICE
- Competition with:
    - ICE
    - BEV (advanced batteries)
    - PHEV/EREV
- Grid balancing – costs
- Qualification of benefits of H_2 and FC
- Whole system analysis needed to compare options
- Innovation systems
- Legal issues
- Life cycle analysis needed to compare technologies
- Life cycle assessment & sustainability

Environmental impacts

- Environment damage of hydrogen:
    - Upsets atmospheric chemistry (H_2 is leaky)
    - More localised H_2 reduction
    - H_2 release make localised
    - Radicals in atmosphere reduced – ie less available to breakdown pollution
    - Are we introducing something more damaging?
    - Unknown consequences (unknown unknown?)

Role of static FC and H_2 in grid balancing/storage of intermittent generation.

- H_2 as energy storage/carrier
- Balancing grid with H_2
- (Role for H_2) National Grid balancing: economics, market proposition
- Storage/transport heat/power
- Technology that works with intermittent electric
- Electrolysis for demand side participation in grid balancing

Carriers

- Links to LNG or other energy carriers
- Converting H_2 to a more conventional fuel to exploit existing infrastructure
- Using H_2 to 'upgrade' $CO_2 \rightarrow$ fuel

Non FC issues

- Integration of gas and electrical systems
- Safe combustion:
  - Emissions
  - Flash back
  - Flame stability
- Economics of 'blended' gas infrastructures
- Blended gas end use

Systems Integration

- Thermal management - H_2 – Thermal integration with FC
- Dynamics of system are important, including load following
- In-situ monitoring, modelling and control
- Control of SOFC with Biogas
- System integration (whole system, multi sector, cross-cutting)
- Transient response for vehicles ~ 500ms
- System efficiency vs. Load set point. Improving fuel cell system efficiency at higher loads
- System integration into energy system
- Hybrid power train platform
- Dynamic modelling
- System integration
- Fuel Cell system modelling & optimisation
- Dynamic behaviour + control:
  - Stress
  - Electrical network
  - Power electronics
- Thermo-chemical cycle technology improvements
- Integration with thermal storage
- System control strategy – black start/shutdown
- Low-cost H_2 sensors
- On board H_2 purification:
  - Lifetime of PEMFC degraded by impurities
  - Low cost, small system volume metal membranes

Safety

- Training for emergency services
- Safety of on board storage:
  - Indoor release (garages/tunnels)
  - Increase fire resistance of types 3/4 vessels
  - Decrease separation distances by novel PBD
- Safety / toxicity
- Low cost H_2 sensing
- In-situ monitoring & control
- Health & Safety:
  - Initial insurance and assurance

    - Whole life behaviour
    - Vehicle MoT is it enough?
- Low overpressure for safety

Socio-economics and Policy

Public acceptance

- User perceptions/understanding
- Public acceptability
- Outside H_2 'supporters club' who will support/champion H_2?
- Techno-economic and environmental performance
- Demonstrate rigorous sustainability in the H_2-fuel cell chain
- Place + community:
    - Where could/will H_2 happen and why?
    - Spatial dimensions of the infrastructures + use
- Cost – cost efficient H_2 cost of FC
- Safety of indoor use of LH_2 (complimentary to FCHJV project safety use of FCH systems indoors) cost/kwhr per/wt radios
- Public liability & insurance
- Holistic systems approach (govt/public understanding)

Market acceptance

- Market issues
- Policy/incentives needed
- Worldwide certification (transportable/transferrable refilling systems)
- Convincing chemical industry to use more expensive but greener H_2
- Socio-economic system analysis
- Understand factors affecting uptake of H_2FC vehicles
- Identifying appropriate business model for H_2
- Preparing for market introduction is more than H_2 tech development
- Long term fuel policy 2030/2050 targets
- New business model for H_2 paths
- Lease based models
- Cost:
    - Initial costs too high
    - Unclear policy for the drivers of change
    - See health & safety

Understanding the transition

- Fuel cell cost models & cost reduction pathways
- Making links between H_2 for other mobile approaches (PITEV etc)
- Identifying transition stages to develop learning
- H_2 from H_2O demands on H_2O resource: competition with human consumption
- Identifying niche market opportunities that can help drive transition
- Competing uses of renewable fuels
- Synthetic liquid fuels as alternative sciences for future transition
- Infrastructure routes:
    - May be transition stages
    - Lock in chargers

Durability/Reliability

Systems

- Realistic conditions for durability performance test
- System integrity
- Lifetime prediction
- Building 'robustness' into hydrogen system
- Durability of balance of plant components & modules

Diagnostics

- Diagnostic:
    - In-situ
    - Sensors
- Diagnostics – identifying limiting factors
- Environment tolerant diagnostics, particularly steam/fuel
- Durability & diagnostics
- Maintenance (O&N)
- Diagnostics (in-situ)Degradation mechanisms/accelerated testing, theoretical understanding

Materials stability

- Long term materials stability
- Robust durable lifetime
- Durability & degradation
- Longevity/degradation
- Fuel cell durability (operated on syn gas)
- Degradation issues
- Side reactions mechanistic understanding (metrology)
- Develop fundamental theoretical understanding of degradation
- Electrodes:
    - Catalysts
    - Structure
    - Degradation (mechanisms)

Contamination

- Fuel contaminants
- Fuel/solid interaction? Contamination?
- Coated materials to improve durability to O2/H2O/poisons
- Remediation after poisoning?
- Coke formation sulphur poisoning
- Anode materials stable/resistant to impurities
- Cation transport interfaces impurities H_2O

Applications

Non-Fuel Cells Hydrogen

- Domestic H_2 for cooking + boilers (flame stability)
- H_2 – ICE research (low emissions)
- Micro CHP & buildings

Fuel cells applications

- Small mobile applications could be crucial
- H_2 fuel cells e-bikes in China

- Material handling vehicles in USA → fuel cells begin to displace batteries because they bring better benefits (depending on user)
- Portable back-up power/generators
- Fuel cell range/extended electrical vehicles
- HGVs (prime mover)
- Heavy mobile could be crucial 1st application role:
    - Trains (H_2 + Fuel Cells vs. electrification)
    - Ships
    - Bus & HGV early application
    - Niche pioneers fork lift + trucks
    - Military

Fuel

Types of Fuels for Fuel cells

- Fuel flexibility
- Low cost, high efficiency, fuel flexible fuel processors - <u>manufacturability</u>
- Understanding of fuel variability in "real world" (including contaminants)
- Direct carbon fuel cell
- Real-world fuels
- Blended biogas fuels
- Direct ammonia direct urea fuel cells
- LNG – direct feed fuel cells

Production

- Large scale H_2 production (grid scale)
- Flexible, dynamic H_2 prod. & store
- Economical/energy efficient distributed H_2 production
- Basic modelling + hydrogen production and safety (fundamental research)
- H_2 production from fossil fuel + CCS → low emission
- Low temp. Thermo-chemical cycles for H_2 production

Separation and purity

- H_2 separation from production gases
- Purity of H_2 – impact on end users
- High P H_2 production (e.g. high P electrolyse)
- Membrane based purification + combined reaction separation
- H_2 purity

Feedstock

- Variety of feedstock for H_2 production → development of fuel/feedstock – flexible H_2 production processes
- Biological waste – links to storage
- Biological H_2 production
- H_2 generation from waste and bio routes
- H_2 production from sustainable low C sources e.g. waste, biomass
- 'Green' H_2 production (means 'green' all down the chain to end use)
- Low C routes to H_2:
    - Electrolysis
    - Materials
    - Catalysts

- H_2 from renewable sources. → water splitting?
- H_2 from sea water (materials)
- H_2 generation via solar routes

Electrolysis

- H_2: high performance safe electrolysis
- High temp. Electrolysis
- Fundamental understanding electrolysis mechanisms
- Microbial electrolysis
- High pressure electrolysis H_2, (O_2)

Distribution and infrastructure

- Fuel production distribution + infrastructure
- Green H_2 (critical to 'sustainability' claims)
- Integration of delivery. storage use
- Infrastructure refuelling – is slow → refueller recharge
- Decarbonised manufacturing – distribution – use system
- Compression – higher efficiency, lower cost, for filling stations e.g. ionic liquids, metal hydride compressors
- Making H_2 distribution system robust.
- Scale, temporal, spatial

Storage

Storage systems

- H_2 storage cost models & cost reduction pathways (?)
- Hybrid designs storage systems
- Safe handling of materials
- Durable materials
- Different infrastructure issues incl. safety codes and regulations for different on-board storage options:
    - Compressed gas
    - Different liquid fuels on-board reforming
    - Solid state
    - Complementarities and irreversibility
- Use of H_2 in confined spaces – safety
- Fundamental H↔storage host interactions
- Simulations and modelling of H-store regeneration reversibility
- On-board reforming liquids/gases
- Small scale storage/cartridges for portable applications
- Storage optimised for static app.

Solid state

- Engineering solid state stores
- Reversible high capacity storage materials
- Storage materials high energy density 780g H_2/ltr
- Compressed - gas and solid – state hybrid store for H_2
- Solid state/liquid H_2 carriers
- Enhanced sorption catalysts for H_2 storage and FC

- H_2 chemistry for reversible/high capacity storage
- H_2 storage → multi functional storage/mechanical thermal materials
- Materials with high reversibility

Compression
- Compression
  - e.g. ionic
  - Less energy than mechanical/current options
- Low cost compression
- Alternatives to expensive 700 bar tanks
- Safe low cost H_2 storage

Infrastructure/Supply chain
- H_2 storage supply chain (Tier 1s)
- Infrastructure evolution & optimisation

Vectors
- H_2 storage → via liquid vectors NH_3, CH_4, ...
- Novel storage (liquid carriers of H_2). Synthetic liquid fuels
- NH_3 for H_2 storage
- H_2 into other form of liquid fuel/energy

Cryogenic/liquid storage
- Low temperature and high capacity H_2 – storage material
- Cryogenic-compressed storage to avoid boil-off of H_2
- LH_2-storage (20k) cooling
- On board small liquefiers of H_2
- Small scale efficient liquefaction of H_2

Large scale
- Geological locations for large scale H_2 storage
- Large scale storage

Materials
- Steam tolerance of materials (acceptable levels/performance trade off)
- Mechanical integrity:
  - Basic understanding
  - Self healing
  - Composites
- Electrolytes:
  - Low temp range
  - Lower cost
- Structure optimisation
- Cost reduction:
  - Materials
  - System BoP
- Molten anode fuel cells for fuel flexibility
- SOEC:
  - Electrode material
  - Electrode microstructure

- Electrolytes (and production)
- Intermediate T

- Materials for electrolysers (low T & high T)
- Materials for higher performance
- Energy carrier (H^+, e^-) transport in materials
- Reversible ORR cuts. Non-metal?
- High temp and materials degradation
- Fuel flexibility:
    - Gas conditioning
    - Fuel processing/cleaning
    - Dynamics
- Sealing issues at high temperature
- Theoretical research into materials stability + function
- Stable non-carbon supports
- Stable carbon supports
- End of life resource availability
- Biofuel cells:
    - Lots of feedstock options
    - Not for electricity generation per se, more for energy efficient waste treatment
- Impact of gas impurities
- New classes of electro-catalysts for low-T applications
- New catalyst for PEUFC cost-effective and durable electrolyte membranes
- Novel functional materials, nano-composites
- Durability and operational safety/cost
- Mitigation of fire and explosion hazards
- Delivering high fuel utilisation → efficiency
- Fuel crossover
- Mechanical integrity fuel/temperature cause
- New materials high activity high durability
- Redox, high VF efficiency

People issues

- UG + PG + PDRA training
- Strategic training - /early career fellowships in HFC
- Flexible **CDTs** – allow BROAD fellows of DTC/EngD programmes
- Retaining critical research capacity with shrinking budget
- Mechanisms to recruit the best talent worldwide
- 5 year fellowships for Postdocs/Early career
- Cryogenic – not enough people trained here
- Safety
- Education – (under and post graduate) not only "training"
- Educational toys

Comments not fitting the above categories

- What does H_2-based mobility do more than electricity based one? What relevant issues?
- Cost & manufacturing
- Manufacturability
- Advanced manufacture techniques (cost, capacity, speed)