Research Councils UK Energy Programme Strategy Fellowship

Summary of Expert Workshop on

Electrochemical Energy Technologies and Energy Storage

Working Document

August 2013

This is a report of a workshop held to support the development of the Research Councils UK Energy Research and Training Prospectus at St Hugh's College, Oxford on 25-26 June 2013

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Research Councils Energy Programme

The Research Councils UK (RCUK) Energy Programme aims to position the UK to meet its energy and environmental targets and policy goals through world-class research and training. The Energy Programme is investing more than £625 million in research and skills to pioneer a low carbon future. This builds on an investment of £839 million over the period 2004-11.

Led by the Engineering and Physical Sciences Research Council (EPSRC), the Energy Programme brings together the work of EPSRC and that of the Biotechnology and Biological Sciences Research Council (BBSRC), the Economic and Social Research Council (ESRC), the Natural Environment Research Council (NERC), and the Science and Technology Facilities Council (STFC).

In 2010, the EPSRC organised a Review of Energy on behalf of Research Councils UK in conjunction with the learned societies. The aim of the review, which was carried out by a panel of international experts, was to provide an independent assessment of the quality and impact of the UK programme. The Review Panel concluded that interesting, leading edge and world class research was being conducted in almost all areas while suggesting mechanisms for strengthening impact in terms of economic benefit, industry development and quality of life.

Energy Strategy Fellowship

The RCUK Energy Strategy Fellowship was established by EPSRC on behalf of Research Councils UK in April 2012 in response to the international Review Panel's recommendation that a fully integrated "roadmap" for UK research targets should be completed and maintained. The position is held by Jim Skea, Professor of Sustainable Energy in the Centre for Environmental Policy at Imperial College London. The main initial task is to synthesise an Energy Research Prospectus to explore research, skills and training needs across the energy landscape. Professor Skea leads a small team at Imperial College London tasked with developing the Prospectus.

The Prospectus will contribute to the evidence base upon which the RCUK Energy Programme can plan its forward activities alongside Government, RD&D funding bodies, the private sector and other stakeholders. The tool will highlight links along the innovation chain from basic science through to commercialisation. The tool will be flexible and adaptable and will take explicit account of uncertainties so that it can remain robust against emerging evidence about research achievements and policy priorities.

One of the main inputs to the Prospectus is a series of four high-level strategic workshops and six in-depth expert workshops taking place October 2012- July 2013. Following peer-review, the first version of the Prospectus will be published in November 2013 and will then be reviewed and updated on an annual cycle during the lifetime of the Fellowship, which ends in 2017.

This document reports views expressed at an expert workshop held in June 2013. Views expressed are noted by the Fellowship team but not all will necessarily be endorsed in the final version of the Energy Research and Training Prospectus.

Contents

List of Acronyms

BIPV	Building-integrated photovoltaics
BIS	Department for Business, Innovation & Skills
CCS	Carbon Capture and Storage
DC	Direct Current
DECC	Department of Energy and Climate Change
EPSRC	Engineering and Physical Sciences Research Council
ESRC	Economic and Social Research Council
ETI	Energy Technologies Institute
EU	European Union
ICT	Information and Communications Technology
IEA	International Energy Agency
IOM3	Institute of Materials, Minerals and Manufacturing
IP	Intellectual Property
KTN	Knowledge Transfer Network
LCA	Life Cycle Assessment
NERC	Natural Environment Research Council
PV	Photovoltaic
R&D	Research and Development
RCs	Research Councils
RCUK	Research Councils UK
RD&D	Research, Development and Demonstration
RSC	Royal Society of Chemistry
SOFC	Solid-oxide Fuel Cell
STFC	Science and Technology Facilities Council
TRL	Technology Readiness Level
TSB	Technology Strategy Board
UKERC	UK Energy Research Centre

1. Overview

This document summarises the outcomes of a workshop held on 25-26 June 2013 in order to identify research and training needs relating to electrochemical energy technologies and other forms of energy storage. Most of the technologies considered are underpinned by materials science and chemistry. In terms of scope, the workshop covered the follow areas, defined under the EU/International Energy Agency (IEA) energy R&D nomenclature:

- photovoltaics;
- hydrogen storage;
- fuel cells;
- energy storage; and
- solar fuels.

The workshop was organised with input from Deirdre Black of the Royal Society of Chemistry, Stuart Irvine of Glyndwr University and the Institute of Materials, Minerals and Mining (IoM^3), and Jenny Nelson of Imperial College London.

There were 28 participants at the workshop (excluding the Fellowship and facilitation teams), most of whom were academics and researchers falling within the community supported by the Engineering and Physical Sciences Research Council (EPSRC) and the Science and Technology Facilities Council (STFC). In addition, there were two private sector participants.

The meeting was professionally facilitated by the Centre for Facilitation Services Ltd in association with the RCUK Energy Strategy Fellowship team. This record of the meeting constitutes a working document, intended to capture the outcomes of the workshop. It represents an intermediate step in the production of a full Energy Strategy Fellowship report, which will set out the prospectus for energy research and training needs relating to energy infrastructure. It has two purposes; a) to provide a resource which can be 'mined' in order to produce the prospectus document; and b) to provide an account of the workshop for comment by the participants and for archival purposes. View expressed are not necessarily those of the Fellowship team.

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2. Introductory Presentations and Participants' Reactions

To familiarise workshop participants with the context for and the purpose of the workshop, Aidan Rhodes made two introductory presentations. The first of these outlined the rationale behind the RCUK Energy Strategy Fellowship and key activities, noting the role of the Prospectus in informing the future design of the RCUK's Energy Programme. He explained how the *Electrochemical Energy Technologies and Energy Storage* workshop formed part of a wider programme of work being undertaken through the Fellowship, including five other expert workshops, three strategic workshops and three light touch reviews.

The second of the presentations provided a summary of the three strategic, cross-cutting workshops that preceded the Energy Infrastructure workshop.

2.1 Strategic Workshop 1: Energy strategies and energy research needs

A key message from the first workshop on *Energy strategies and energy research needs* was that people's expectations about progress towards a low carbon economy lagged behind what they thought was desirable. Focusing on electricity supply technologies, people expected the deployment of wind, marine renewables and PV to fall below desirable levels by 2050 while the use of unabated gas generation would be correspondingly greater.

The participants of this workshop concluded that UK scientific capabilities with respect to hydrogen and fuel cells were high while capabilities with respect to energy storage research were in the middle of the range internationally. Nevertheless, energy storage was seen to be highly relevant to UK energy futures and industrial capabilities in the UK were felt to be relatively strong with much left to play for internationally. Hydrogen and fuels cells were felt to be less relevant to UK energy futures. In terms of industrial capability, fuel cells were seen to be in the middle of the range but relatively low.

2.2 Strategic Workshop 2: The Role of Environmental Science, Social Science and Economics

It was difficult to present high-level conclusions from the second strategy workshop on the role of environmental science, social science and economics, but some "nuggets" were presented:

- A disproportionate effort has been put into kit as opposed to behaviour;
- There is an over-reliance on economics in the design of energy policy;
- Promoting energy demand research was like Sisyphus pushing his stone up the hill;
- Instrumental social science that helps answer policy questions is popular with funders but it rests on a foundation of fundamental, critical work;
- Language matters, but natural scientists often form the view that a social scientist's first question when approaching a subject is to question terminology and meaning; and
- Research Councils can and have forced better interdisciplinary working.

2.3 Strategy Workshop 3: The Research Councils and the Energy Funding Landscape

This workshop explored the role of the Research Councils within the wider energy innovation landscape. Two representative case studies were used to facilitate discussions: marine renewables, an example of use-inspired research, where policy and end-user goals drove the research effort; and molecular photovoltaic research, which was inspired more by basic science. Some key findings were:

- **Basic Research:** There need to be stronger mechanisms for feeding findings from later in the innovation process back to basic research projects.

- **Scope of the Research Councils:** At which point should the handover between the RCs and the later innovation bodies (ETI, TSB) occur?
- **Applied R&D:** There is a need for adaptable and flexible testing facilities and development centres, and for ensuring spin-out companies can understand and access their potential markets.
- **Pre-commercial Deployment:** Clear policy signals and market regulations are needed so that investors feel secure.

A key finding from the workshop was that it is important to have a clear long-term vision alongside a research programme, signalled by market, government and regulatory policies.

2.4 Participants Reactions to Strategic Workshop Results

Participants were then asked to record their reactions to the outcomes of the strategy workshops under three headings: what surprised, delighted and disappointed them. These were discussed in nine table groups. The outputs are recorded in Table 1.

Following this, groups were asked to highlight some key points which they thought were important highlights of the discussion.

Group 1 felt that surprises were lacking, were delighted that the analysis was starting but were disappointed by the lack of transformative ideas emerging from the strategy workshops.

Group 2 was surprised at the low level of expectations for solar thermal and storage, delighted by the diversity of technologies covered and disappointed by the low level of expectations for renewable energy.

Group 3 was surprised by expectations about CCS for the long term (when this will be expensive and is a short term solution), delighted to see that the link between research and the development of technologies is recognised, but disappointed by lack of consideration given to the integration of renewable energy into the grid.

Group 4 was surprised at the long term vision but noted that this was not seen in funding calls, delighted with the range of topics and discipline being looked at, but disappointed that the strategy was not available to everyone (only people in this room).

Group 5 was surprised that people expect a continuing large deployment of high-carbon technologies, delighted by the point that interdisciplinary work is not in line with academic incentives, but disappointed at the lack of consideration of how technologies fit together.

Group 6 was surprised at what they considered the overestimation of the UKs current industrial capability, delighted to see caution about the lack of career paths and disappointed at the lack of linkages to technology in the socio-economic workshop.

Group 7 was surprised by the degree of consensus, delighted that basic science had attracted consensus, but disappointed that funding constraints and bottlenecks prevented the resolution of big problems.

Group 8 was surprised by the lack of emphasis on energy storage, delighted to see economics being looked at but disappointed at the lack of follow through.

Group 9 was disappointed at: the limited engagement with policymaking (e.g. DECC); limited opportunities for international activity being identified; and misunderstanding of hydrogen.

Table 1: Participants' reactions to the results of strategic workshops.

Surprise	Delight	Disappointment
General		
Lack of surprises	That this analysis exists at all	Lack of imagination – (particularly given 2050 timescale)
No real surprises	The issues are finally being generally discussed and thought about	Not very imaginative regarding the mechanisms of how to achieve goals
Long-term/wide-range thinking displayed	Some effort is happening	Lack of ambition/vision
That any significant consensus was realised	Holistic – broad range of people/subjects queried	Lack of a definite ambition (incentives to deal directly with problems)
Seems to describe problems not solutions	Workshops seem to address most key energy topics	That the outcomes were not more specific in terms of recommendations
Social scientists better at defining questions and methodology	Broad range of people/subjects queried	No long-term strategy/follow-through
	Attempting the difficult task of comparing different energy systems	Lack of tailored solutions
	Some coherent messages	Inevitable parochialism from different disciplines/areas
	That some themes, including basic research, attracted consensus	
	To be at this workshop!	
	Not a lot to delight!	
	None	
	That there is a perception that DECC is over-reliant on economists	
	Over-reliance on economics	
The Process		
The timing of this seems "behind" current funding calls		This process (strategy review) does not seem visible enough
Don't see much input from DECC		
Not so much industrial/commercial perspective (especially from large companies		

Surprise	Delight	Disappointment
Applied and blue skies research; commercialisation		
That the "pull" or market for research was not mentioned much	Acknowledgement of the challenges faced in balancing strategic and blue skies research	Not much industry/no path to commercialisation
Limited engagement with policy/industry - DECC, TSB, large companies	Address challenge of moving from laboratory to technology	No solution to the "valley of death" TRL problem
	Need for research programme to align with application	Little involvement of industrial technology developers in renewables strategy
	Mention of applied work	
The Projected Energy Mix		
Workshop's expectations of energy supply profile	Strong low carbon agenda	Expected 2050 mix for electricity – what about other energy needs?
Over-reliance on carbon-based fuels	Diversity of options and opportunities for technologies in UK context	Lack of expectation that electricity supply will be transformed by 2050 – still large conventional component expected
Such a high expectation for CCS – goes against energy efficiency		Amount of high carbon energy sources in 2050 predictions
		Wide range of supply technology shares
		Total lack of precision in technologies bar chart!
Technologies within the workshop scope		
Low expectation for solar thermal	The importance given to the energy storage area	Roles of electrochemists
UK low international standing in bioenergy and hydrogen/fuel cells	Electrochemical energy storage is highlighted!	That the potential for solar PV in the UK is not recognised
Wide difference in opinion over hydrogen/fuel cells capability	Energy storage high on agenda	Lack of understanding of hydrogen as energy storage
Fuel cells so low in rank	Some themes including basic science attracted consensus	Lack of mention of hydrogen or alternative fuels
Low rating of storage technologies		Decreased interest in fuel cells
Little recognition of storage in electricity technology market review		Batteries not mentioned explicitly
Lack of treatment of issues arising from intermittency		
No mention of materials research/challenge		
Consensus, no materials challenge		

Surprise	Delight	Disappointment
Research portfolio and technologies outside the workshop scope		
CCS is so strongly preferred	Diversity of options and opportunities for technologies in UK context	Pure focus on technology silos – no consideration on how things come together
Such a high expectation for CCS – goes against energy efficiency	That a wide range of technologies and perspectives were considered	That the belief in CCS at such a high level when still unproven at scale
Relatively low position of CCS and marine in "no clear lead" category	Wide range of technologies considered important	
Offshore development in the UK?	That all technologies are still considered, including system/deployment research	
Lack of recognition of role of large corporations to take new technologies forward		
Training and career progression		
Academic career progression seen as a barrier: knowledge transfer (KT) highly prioritised at some institutions	Need for career path for skilled workers beyond personal development and recognition programmes	
	Lack of career paths identified	
International and the UK's standing		
Overestimation of the UK's true industrial capability	Recognise strength of UK research	Focus on UK energy systems – may miss international connections and opportunities (research, economic, environmental)
No consideration of international frameworks when it comes to market shares	Lots of UK strengths/potential identified	Focus on UK energy systems – no international connections/opportunities
That there is the perception of the UK having a substantial industrial advantage in energy storage		
Interdisciplinarity		
	Acknowledgment that interdisciplinary working can (complement traditional academic projects)	Lack of solution to "babelfish" problem
		Interdisciplinarity still not valued
		Comment that interdisciplinary funding/prestige is a challenge
		Discipline-based comments from socio-economic workshop – behaviour is not energy-specific
		Better linkages between "nano" and "social" sciences not identified

3 Helicopter View of the Research Terrain 'as-is'

Aidan Rhodes from the Fellowship Team began this section by presenting a diagram showcasing basic concepts of the electrochemical energy and energy storage sectors, listing the vectors of energy delivery against key processes in harvesting, converting and storing energy. The major electrochemical and storage technologies were plotted on the table below. Italicised technologies are ones which are electrochemical in nature.

Vectors / Processes	Electric	Heat	H_2 and other Fuels	Kinetic
Harvesting (From the wider environment to controlled energy vectors)	***Solar PV***	Solar Thermal	***Solar Fuels***	
Conversion (From one energy vector to another)	***Fuel Cells***	***Fuel Cells***	***Fuel Cells*** ***Electrolysis***	
Storage (Storing an energy vector)	***Batteries*** ***Supercapacitors***	Thermal Storage ***Phase-change Materials***	***Hydrogen Storage Materials*** Compression and Cyrogenics	Flywheels Pumped Hydro Compressed Air Energy Storage

Figure 1: Diagram of key concepts in electrochemical energy and storage.

The participants were then divided into table groups, and asked to prepare a briefing on the energy infrastructure research terrain as it is now. The participants were allowed a short time for individual reflection before feeding their insights into a group discussion. The group than distilled what they considered as the 'key themes' onto post-it notes, which they arranged on a wall chart according to the x-y axes used in Figure 1.

Table 2: Summary of the Review of the Research Terrain "as is"

	Electric	Heat	H_2 and Other Fuels	Kinetic
	Specific targets in research areas	Long term – how does materials research feed into device manufacture?		
Harvesting			Improve/develop photocatalyst for water splitting.	
	Looking at the supply chain: Materials -> Device cost -> System cost -> Long-term energy + Durability = <u>cost of energy.</u>			
	Low-cost materials-devices-systems			
		Systems integration + control. Storage + application + generation.		
	Materials for Li-ion Next-gen batteries – Li-S/Li-Air New batteries. Eng+Geometry. -> Redox flow -> Structured Electrodes			
Conversion				
	New materials for fuel-cell/battery technology. Research is strong.		Cost/value strategic drivers	
		Academics pushed to pre-industrial research.	Lack of long-term strategy	
	Batteries: Resources – Minerals. Issue of scale of electrochemical energy devices	Sustainability. Use of strategic materials. Technology selection.	Lack of applied research institutions (Fraunhofer).	
Storage	EC storage: cost reduction, safety improvements			

Each group was given two minutes in plenary to present the key themes from their discussions. The following is a distillation of the table discussions and the plenary presentations, focusing on the main emerging themes.

- Technologies in this area need to be a great deal more durable. They need to be able to last under standard conditions for at least ten years. Costs of devices also need to come down, driven by research into low-cost materials, systems and devices. The value of a device is more important than its upfront cost – it needs to provide a proposition significantly improved from conventional devices.
- There needs to be good management of strategic materials (e.g. lithium, rare earths, platinum), including steps to recycle used materials and manage supplies of these materials on a global scale.
- Taking discoveries in materials science and incorporating them into engineering solutions is essential. It requires stability in policymaking to succeed, as many of these efforts are over the timescale of years.
- The scaling up of electrochemical storage and fuel cell technologies is a key issue. Battery technology is widely used on a small scale in portable electronic devices, but scaling these technologies up to a large grid-scale energy storage unit is not a simple task. Particular attention needs to be paid to battery chemistry – what works well on one scale may not work well on another.
- Hybrid systems, which incorporate two or more technologies working together, can be a useful way of finding niches for technologies, allowing them to enter the market on a small scale. This can help to build up the expertise and supply chain required to more fully exploit the technology. Batteries for hybrid vehicles are an example of this.
- Long-term stability in policy and support was identified by several groups as a key issue, due to the length of time required to develop and commercialise a new technology. Imagination in developing policy was seen as a key asset. Policy should encourage research groups to cooperate more instead of competing, as the work that is done is often very complementary.

4 How well placed are we to tackle existing research challenges in electrochemical energy?

Working individually, people were asked to identify how well placed the UK is currently in terms of electrochemical and storage energy research capabilities so that we can meet the challenges of the future. They were invited to score these on a scale of 0-10 (0 = no chance, 10 = well set up) and explain their score on a post-it note. Figure 2 shows the distribution of the 24 post-it comments.

This represents a distributed and somewhat lower set of scores than many of the other workshops, with a tight cluster forming between 3-5 and a strong set of responses at 7. The average of the results was 5.6, with a spread of ±2.2. No-one assigned a lower score than 2 to our capabilities. A very strong theme emerging from the comments is the relative strength of the UK's fundamental science in the sectors under discussion coupled with perceived weaknesses in research translation and application. The lack of focus on interdisciplinary studies and 'siloed' research were also commented on. A consistent theme was the perceived lack in long-term and commercial support.

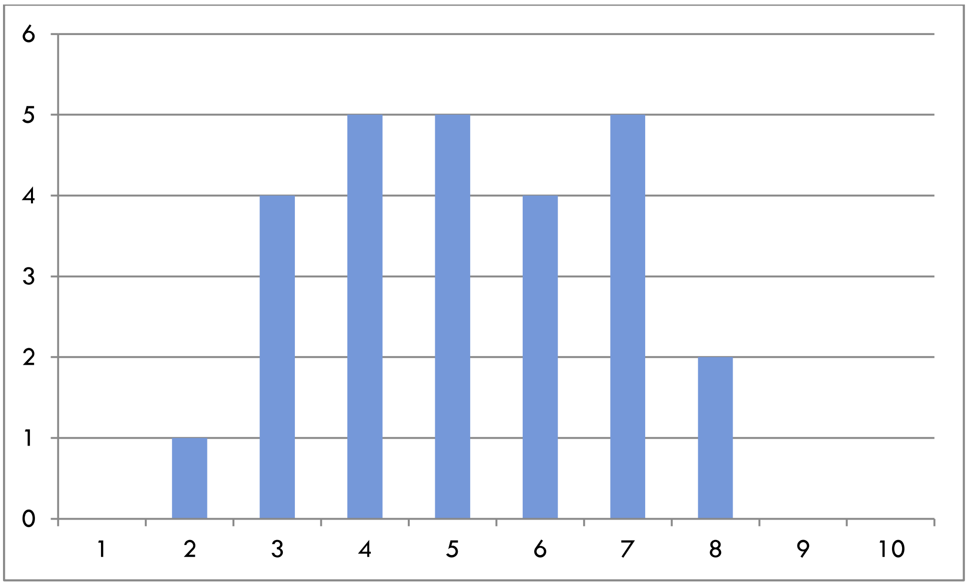

Figure 2: Distribution of perceived UK electrochemical and storage energy capabilities

<table>
<tr><th colspan="3">High capability levels</th></tr>
<tr><th>7</th><th colspan="2">8</th></tr>
<tr><td>Good materials work and systems engineering, BUT needs more manufacture/industry input & policy support,</td><td colspan="2" rowspan="2">High experience and capabilities, worldwide recognised research groups</td></tr>
<tr><td>Research especially in energy materials is good, but support to carry through to application is missing.</td></tr>
<tr><td>Strong academic base but less large company support</td><td colspan="2" rowspan="3">Absence of a strong manufacturing industry</td></tr>
<tr><td>For cryogenic energy storage) capability in materials and process, needs to scale-up to maintain lead.</td></tr>
<tr><td>Good research, nowhere for it to go</td></tr>
<tr><th colspan="3">Medium capability levels</th></tr>
<tr><th>4</th><th>5</th><th>6</th></tr>
<tr><td>Until recently energy storage was a low priority with limited funding</td><td>Excellent quality of human capital but funding historically poorly structured but changing maybe?</td><td>Research good but scattered and patchy, implementation an issue</td></tr>
<tr><td>Limited long-term strategy, poor links between scientists, engineers and industry</td><td>Some world leading research but poorly linked to application</td><td>Lack of pull-through, overseas exploitation likely</td></tr>
<tr><td>Too diverse, not coordinated, no long-termism in funding, researchers are better than they seem!</td><td>Lack of sufficient strategic funding But potentially 10 based on quality of UK research base.</td><td>Small but strong academic community, weak supply line from academics to industry, under-represented, under-strength UK industrial base.</td></tr>
<tr><td>Lack of basic research infrastructure at all levels, lab and large-scale</td><td>Strong research groups but issues regarding funding cuts/postgrad training capacity/translation of research into products.</td><td>High expertise, low industrial support/long term support</td></tr>
<tr><td>Strong international competition, no UK national labs (like Fraunhofer, AIST, DOE)</td><td>Good scientists but lacking critical mass, lack of equipment</td><td></td></tr>
<tr><th colspan="3">Low capability levels</th></tr>
<tr><th>2</th><th colspan="2">3</th></tr>
<tr><td rowspan="4">Challenge is huge!</td><td colspan="2">Inconsistency, lack of determined long-term strategy and realistic/ appropriate funding compared to competitors</td></tr>
<tr><td colspan="2">Strong academic research but weak industrial capabilities</td></tr>
<tr><td colspan="2">Lack of industrial base to drive research</td></tr>
<tr><td colspan="2">Insufficient setting of research targets and funding, no coordination</td></tr>
</table>

5 Research 'Hotspots' and Broader Themes for Future Energy Research

5.1 Introduction to the Exercise

This exercise was designed to identify a range of topics that participants believed should be the subject of future UK energy research and which should therefore constitute an important part of the RCUK Energy Strategy Fellowship's *Research Prospectus*.

5.2 Methodology

5.2.1 Overview

In order to identify future energy research opportunities for the UK in the field of electrochemical energy technologies and energy storage, the participants were first invited to identify 'research hotspots' that could provide valuable insights, should (further) research be conducted into them. A 'research hotspot' was defined as follows:

> 'A ***Research Hotspot*** is a potentially valuable area of future research, which has been identified by the Expert Workshop participants. It is an area in which the experts believe research challenges will emerge in the future. It may be a broad and overarching question or problem'

To help guide the participants, a couple of good-practice examples of hot spots were presented from the *Fossil Fuel and* CCS workshop.

5.2.2 How were the research hotspots generated?

The first part of the process involved the participants working individually to generate initial ideas about potential hotspots. In the second part, participants formed pairs to discuss and record these hotspots. These were recorded on post-it-notes.

Once the pairs had discussed and recorded the hotspots they were then asked to place these on a matrix wall chart, which incorporated similar axes to those used in Helicopter View of Research Terrain 'As-Is' exercise (see Table 2). The axes served to guide participants in placing their hotspots, with a view to subsequent clustering. In practice, participants identified a set of hotspots that were not captured by this matrix configuration and a separate category – "broader hotspot" – was identified.

The participants browsed the wall chart to develop a feel for the research hotspots that others had generated. They were then prompted by random image cards to identify any further research hotspots that might have been omitted. At the same time, participants were encouraged to comment on existing hotspots. This resulted in a noticeable increase in the numbers of hotspots and comments.

5.2.3 Clustering hotspots for different technology applications

During the clustering exercise, participants grouped together similar hot spots in order to create research clusters representing potentially important energy infrastructure research themes. The clustering was performed by three groups corresponding to three broad, technology application categories emerging from the hotspots exercise. These were:

- PV
- Fuel cells and hydrogen
- Other technologies and broader issues.

Once the groups had clustered the hotspots, they then named them clearly and concisely in a way that would be meaningful to non-experts. Each group was assisted by a facilitator who ensured that each member of the group had the opportunity to provide input and that the groups had clustered all their hotspots within the time available.

5.2.4 Grouping the Clusters Together

Participants then worked together in plenary to aggregate the research clusters into ‘super-clusters’. Each group shared one of their clusters with the other groups, who were encouraged to identify any related clusters. Using a system of green, red and yellow cards, participants could confirm their support for a super-cluster (green), veto it (red) or provoke further discussion (yellow). While a number of potential super-cluster arrangements were suggested by the participants, more often than not these were rejected by one or more of the group because they were uncomfortable with further aggregation.

5.3 Results

In their three groups, the participants had grouped the large number of research hotspots into 17 clusters which had been aggregated into 15 ‘super-clusters’, as described above. These 15 super-clusters are summarised in the tables below, along with the associated clusters and specific hotspots.

In addition, two suggested hotspots were deemed to be out of scope: devices for medical environments; and acoustic temperature measurements (more precise temperature monitoring of engines, combustion etc. to reduce energy waste by inefficient processes). Six further suggested hotspots were deemed to refer to research “process” and would be captured in the discussions on Day 2: take risks (anything is possible if you try); open data/innovation (complex international problems); long-term massive scale funding (> 10 years, > £15m); what problems will we encounter that we don't realise are there; collaborative research projects; and improving workflow modelling and discovery to lab/pilot scale, to industrial systems, to commercial reality).

Cluster 1 – Economic and political issues

Cluster Name(s)	Hotspots
1 –Economic and political issues	– Solutions currently too expensive but if developed could be made viable – see history of transistors – Need to persuade politicians and funders that this issue is important enough for long term funding. – Can’t operate on 5 years timescales. Need stability for early career researchers. Need long-term funding for big projects – Training should be included (maybe there implicitly in workshop process). – Is this something we can research into? Elements require research, but not by us. But the final report must address this issue.

Cluster 2 – Sustainability issues

Cluster Name(s)	Hotspots
2a – Green issues	- Earth abundant alternatives to current and future technologies - Life cycle embedded energy of whole systems for specific applications (usage, lifetime etc.) - Recycling and use of scrap materials - Thermo-electric devices efficiency (ΔG, ~T) - "Green approaches" - Recycle/capture/burn – which is best? - Wider environmental impacts of new technologies
2b – Safety , durability and lifetime	- Safety of large battery systems - Durability of devices/components/system - Safety issues – is the energy density we want inherently safe? Economic and user implications. (not just batteries –in PV module operating conditions most common failure is arcing.
2c – Cost reduction	- Cost reduction of solid oxide fuel cells (SOFC) - Cost of lithium ion batteries - Reduce cost and improve performance of batteries for domestic use (especially power density)

Cluster 3 – PV and hybrid system integration

Cluster Name(s)	Hotspots
3 – PV and hybrid system integration	- Systems RD&D – complexity and hybridisation - Variety of technologies is needed - PV coupled with storage, e.g. battery; capacitor; chemical fuel - Safety, durability standards and quality assurance - economic Network management forecasts – looking at technology options and how they work together to meet specific user demands - Hybrid technologies – combination of optimum mixes of technologies for different applications - Integrated solar electric and storage technologies - Mimic natural processes for smarty and scalable technologies

Cluster 4 – Energy systems

Cluster Name(s)	Hotspots
4 – Energy systems	- Energy storage – short-term to manage supply and demand; micro-storage - Generation and storage solutions for off-grid electricity - More distributed generation demonstration - Scalable devices – distributed storage and capture - Localisation of energy generation and storage: energy independence of communities/households; bottom-up approach; dual use of storage - Functionalising building materials external - Functionalising building materials for energy harvesting, storage and lighting - Challenges of urbanisation (smart cities, distributed storage) - Distributed energy control systems - Integrating technologies into whole energy system - Develop plans for what a robust total renewable energy system looks like: balance of renewables; smart grid; storage; demand management; gaps?

Cluster 5 – Hybrid systems

Cluster Name(s)	Hotspots
5 – Hybrid systems	- Heat management integration (for all generation) - "dual use" of storage between transport and grid (e.g. vehicle-to-grid, V2G) - Hybrid synthetic-bio systems - Thermodynamic plus heat transfer processes (in storage subsystems and with other processes) - Is there an optimum hybrid battery–hydrogen light duty vehicle for future low carbon systems - Hybrid technologies, e.g. reversible fuel cells/electrolysis? - Innovative ways of managing energy flows – energy storage can take many forms (e.g. train braking, charging grid at station, regenerable braking)

Cluster 6 – Materials for PV devices

Cluster Name(s)	Hotspots
6 – Materials for PV devices	- New materials for photon capture - Mimic natural materials - Scalable materials synthesis for new materials and nano-materials - Durability and safety - Consider all wavelengths from the sun- how to capture photon energy? - Standards and quality assurance - Cell engineering for material systems - Durable low cost and low energy PV materials - PV materials: stable; printable; earth abundant; non-toxic

Cluster 7 – PV modules and manufacturability

Cluster Name(s)	Hotspots
7 - PV modules and manufacturability	- Identifying bottlenecks in emerging technologies – research targets - Taking new lost cost materials to high efficiency devices - Concentrating solar power (link to existing industry); concentrated PV (IPE Stuttgart) - Manufacture and large scale system level implementation, especially for new technologies - New systems architecture for energy infrastructure on all scales - Transparent electrodes for solar panels, display, lighting etc. - Module engineering - Safety, durability, standards and quality assurance - Manufacturability and packages

Cluster 8 – Other storage approaches

Cluster Name(s)	Hotspots
8 - Other storage approaches	- In a 50-year timeframe, new materials and device structures (disruptive as well as incremental) will be important - CO_2 as an energy vector? $CO_2 + H_2$ -> [HC]. - Seasonal storage (electrolysis driven oxide-element cycles) - CO_2 electrolysis - Ways to utilise marine renewables - Develop efficient gas separation technology - Tethering: development of new gas storage/compression/separation technologies using "undoable" molecular tethers to high surface area materials - Cage structures: storage of charged species of gas molecules using thermally activated molecular cages which open and close at different temperatures - Spatial confinement during cycling

Cluster 9 – Fundamental understanding of materials and interfaces

Cluster Name(s)	Hotspots
9 – Fundamental understanding of materials and interfaces leading to new improved materials (lower cost, abundant, better performance)	- New techniques for studying interfaces under operating conditions (batteries, supercapacitors, fuel cells etc.) - PV materials, interfaces and other fundamental properties - Operational reliability in the field- do we understand the link between materials, production and quality assurance to energy yield "in the field" - Understanding material degradation in electrochemical devices – feedback into improved into **???** design for improved lifetime - Improving the longevity/robustness of solid oxide fuel cells (tolerance to **?????)** - Ion transport in materials: dynamics, interfaces and structure - Electrocatalytic materials: stable; earth abundant or renewable; good catalysts - Rational design (e.g. simulations) of electrochemistry and architecture/morphology of sustainable energy storage systems (e.g. materials and lifetime) - Non-precious metal catalysts for polymer fuel cells - Finding alternatives to critical materials (e.g. platinum group metals – PGMS; rare earths for batteries; fuel cells; permanent magnets etc.)

Cluster 10 – Future Lithium-air and metal-air batteries

Cluster Name(s)	Hotspots

Cluster Name(s)	Hotspots
10 – Future Lithium-air and metal-air batteries	- Recycling/re-use/sustainability of "modern" batteries (e.g. lithium-ion, is it worth recycling?) - Increasing performance of low temperature rechargeable metal-ion/metal-air batteries (emphasis on lithium-ion and lithium-air) - Increasing energy density beyond the lithium-ion limit - Make the lithium-O_2 battery a commercial reality - Proof of concept for lithium- or sodium- air batteries as a viable commercial solution - New battery architectures, manufacturing and fabrication routes, e.g. lithium-ion flow hybrid battery - Magnesium-ion batteries? - Gas (O_2) separation membranes

Cluster 11 – Implementing hydrogen as a sustainable energy vector

Cluster Name(s)	Hotspots
11 – Implementing hydrogen as a sustainable energy vector	- Electrolysis of unpurified water at natural pH - Higher temperature electrolysers – materials and systems to improve rate of oxygen evolution reaction and find a use for oxygen ???? - Sustainable hydrogen production: electrolysis (PV, wind); photocatalytic water-splitting; artificial photosynthesis; photosynthesis - How can we produce low-cost green hydrogen for energy storage and mobile applications - Need high capacity energy store for vehicles (e.g. 9% weight hydrogen store) - Hydrogen feed into natural gas grid. Does hydrogen embrittlement of pipe system, need research? - Massive/long-term hydrogen storage in geology/mines over seasons/years/decades for security in an uncertain future (e.g. climate change) - Making fuel using algae

Cluster 12 – Capacitive storage

Cluster Name(s)	Hotspots
12 – Capacitive storage	- Loss-less capacitors for short- and medium-term charge storage - Hybrid device ("supercapattory" lithium-capacitor) - Fast charge-discharge - Develop vastly improved supercapacitors for power control, transport

Cluster 13 – Issues of scale

Cluster Name(s)	Hotspots

Cluster Name(s)	Hotspots
13 – Issues of scale (time and size)	- More demonstration of large scale energy storage (as in Germany) - Redox flow batteries - Timeliness, e.g. infrastructure elective transportation - Energy storage over different timescales – seconds, minutes, hours, days - Improving cycle life of electrochemical storage (i.e. step change required in cycle life) - Grid-scale storage - Storage – definition of targets appropriate to use (timescale; capacity; chemical bonds versus batteries etc. - Appropriate materials and technologies for large-scale (grid) energy storage (e.g. sodium or lead may be acceptable for grid but not transport)

Cluster 14 – User behaviour and demand

Cluster Name(s)	Hotspots
14 – User behaviour and demand	- Tailor/design products to consumer needs - Demand side management through technology e.g. efficient lighting such as LEDs - Autonomous power at individual level)storage plus conversion) - We may need to change the way we behave as the technology we use - User-centric design of energy storage and energy flow systems in general - Societal challenges – cost, safety - The influence of demographics on energy usage - Improve energy efficiency and reduce waste (still a long way to go)

Cluster 15 – Thermal storage

Cluster Name(s)	Hotspots
15 – Thermal storage	- Low cost thermal storage using cheap, perhaps natural, materials for all grades of heat according to application (but carnot-efficiency limitations) - Improved materials for thermal energy store e- hot and cold – long-term strategic research

5.4 Final discussion

In final discussions, some general points were picked up:

- It is very frustrating when certain technologies are specifically excluded (e.g. hydrogen). There may be optimisation which can include these technologies e.g. in hybrid systems.
- Separating clusters is not always a good idea as there are almost always overlaps. There are dangers in boxing specific issues.
- It is too simplistic to say we need more money for longer – this will always be demanded. UK research budgets are looking increasingly feeble versus international competition.
- Nevertheless longevity is key. Some projects *cannot* be done on short term funding. The demand for long term research is not self-interest but is in the nature of the science.
- People want to be involved in deep dives of their technologies as well as covering cross-cutting issues. Doing the deep dives are is key to understanding.
- If you operate at the super-cluster level, clusters are likely to remain separate since people want to ensure all the issues are recognised as being important. Is the solution a hyper-cluster?

6 Reflections on Day 1

At the beginning of Day 2, participants were asked to work in pairs and consider what had been achieved on Day 1. Had any important issues been missed out? During an open-microphone session, participants had the opportunity to voice any concerns that they felt should be borne in mind during the Day 2 discussions. The following points were raised.

Headline targets are missing. For example, Scotland has a 100% renewable electricity target. Over-arching targets allow all programs to fit in and send a clear message to politicians. Need a single big objective which everyone can buy into. However, it was noted that the UK already has targets. We need to bolt research strategy into this.

Mechanical storage technologies. There has been no discussion of flywheels, pumped hydro, etc.

PEM and solid-oxide fuel cells. The fuel cell community is under-represented considering the scale of research and the number of *companies* in the UK. Fuel cells provide a route to market for research into new materials since a number of companies exist in UK who could exploit research.

Clustering and research strategy. Clustering does not provide an answer to research strategy. It has highlighted a number of topics, but has not identified issues. Working on the clusters is not going to help us move forward.

PhD training. EPSRC has to ensure there is PhD training in place to ensure that skilled researchers are there to deliver over long time frames.

Fuel cells are energy convertors. Combining fuel cells with other technologies (e.g. electrolysis) makes them relevant, but they are energy converters not a storage technology.

High efficiency devices. The challenge is to take new materials from low efficiency devices to high efficiency devices across all technologies. Exciting new materials can make very efficient solar cells but this should be translating to other technologies.

Participation. Disappointed not to see DECC, National Grid or motor manufacturers, as these are the people who will implement future storage.

Expertise in fundamental science. People in the room have very strong collective expertise in fundamental science and materials across these technologies. We should capitalise on this. Keep other issues in mind but not focus on them exclusively.

7 Research Cluster 'Deep-Dive': Communities

7.1 Overview

The purpose of this session was: a) to judge the capability and capacity of 'UK Research plc' to address the research challenges identified in the research clusters identified during the 'research hotspots" session described in section 5; and b) to suggest what needs to be done to address any shortfalls. Participants were invited to address the following questions:

1. What are the main research challenges we need to address for our research to be first class in terms of both excellence and impact?
   - consider immediate/medium term (2030)/long term (2050)
2. To address these what do we need in place, consider for example:
   a. What capabilities/capacities do we need in place?
   b. What needs to happen in terms of coordination and alignment to maximise success? (e.g. PhD training, data collection/curation, facilities, research infrastructure, finding philosophy etc.)
   c. Whose job should it be/who is best placed to do/fund this research?
   d. Economics and political will (referring to cluster 1 which participants felt was of a cross-cutting nature).

7.2 Method

This session covered the scientifically and technically focused clusters identified in the "hot-spot" session described in Section 5. Five clusters – 1, 2, 5, 13 and 14 – addressing cross-cutting or "process" issues such as scale, sustainability etc. were covered in the session described in Section 8.

Participants were initially divided into four self-selected "communities of practice" to assess a first set of research clusters. "Communities of practice" were initiated by individuals who expressed an interest in a particular research theme or approach by writing the topic on a sheet of paper laid out on the floor then inviting others to join them. The aim was to have groups of no more than six people. The communities selected priority clusters but one or two "orphan" topics were allocated to groups by the organisers. The "communities of interest" addressed the research hotspots listed in Table 3. Each group was invited to cover the questions listed in Section 7.1.

Table3: Communities of Interest and their Research Hotspots

Community	Cluster	Hotspot
PV	3. PV and hybrid system integration	- Systems RD&D – complexity and hybridisation - Variety of technologies is needed - PV coupled with storage, e.g. battery; capacitor; chemical fuel - Safety, durability standards and quality assurance - Network management and economic forecasts – looking at technology options and how they work together to meet specific user demands - Hybrid technologies – combination of optimum mixes of technologies for different applications - Integrated solar electric and storage technologies - Mimic natural processes for smarty and scalable technologies
	6. Materials for PV devices	- New materials for photon capture - Mimic natural materials - Scalable materials synthesis for new materials and nano-materials - Durability and safety - Consider all wavelengths from the sun- how to capture photon energy? - Standards and quality assurance - Cell engineering for material systems - Durable low cost and low energy PV materials - PV materials: stable; printable; earth abundant; non-toxic
	7. PV modules and manufacturability	- Identifying bottlenecks in emerging technologies – research targets - Taking new lost cost materials to high efficiency devices - Concentrating solar power (link to existing industry); concentrated PV (IPE Stuttgart) - Manufacture and large scale system level implementation, especially for new technologies - New systems architecture for energy infrastructure on all scales - Transparent electrodes for solar panels, display, lighting etc. - Module engineering - Safety, durability, standards and quality assurance - Manufacturability and packages

Battery storage and distributed energy systems	4. Energy systems	- Energy storage – short-term to manage supply and demand; micro-storage - Generation and storage solutions for off-grid electricity - More distributed generation demonstration - Scalable devices – distributed storage and capture - Localisation of energy generation and storage: energy independence of communities/households; bottom-up approach; dual use of storage - Functionalising building materials external - Functionalising building materials for energy harvesting, storage and lighting - Challenges of urbanisation (smart cities, distributed storage) - Distributed energy control systems - Integrating technologies into whole energy system - Develop plans for what a robust total renewable energy system looks like: balance of renewables; smart grid; storage; demand management; gaps?
	10. Future Lithium-air and metal-air batteries	- Recycling/re-use/sustainability of "modern" batteries (e.g. lithium-ion, is it worth recycling?) - Increasing performance of low temperature rechargeable metal-ion/metal-air batteries (emphasis on lithium-ion and lithium-air) - Increasing energy density beyond the lithium-ion limit - Make the lithium-O_2 battery a commercial reality - Proof of concept for lithium- or sodium- air batteries as a viable commercial solution - New battery architectures, manufacturing and fabrication routes, e.g. lithium-ion flow hybrid battery - Magnesium-ion batteries? - Gas (O_2) separation membranes
Materials and other storage approaches	8. Other storage approaches	- In a 50-year timeframe, new materials and device structures (disruptive as well as incremental) will be important - CO_2 as an energy vector? $CO_2 + H_2 \rightarrow$ [HC]. - Seasonal storage (electrolysis driven oxide-element cycles) - CO_2 electrolysis - Ways to utilise marine renewables - Develop efficient gas separation technology - Tethering: development of new gas storage/compression/separation technologies using "undoable" molecular tethers to high surface area materials - Cage structures: storage of charged species of gas molecules using thermally activated molecular cages which open and close at different temperatures - Spatial confinement during cycling

	9. – Fundamental understanding of materials and interfaces	- New techniques for studying interfaces under operating conditions (batteries, supercapacitors, fuel cells etc.) - Operational reliability in the field- do we understand the link between materials, production and quality assurance to energy yield "in the field" - Understanding material degradation in electrochemical devices – feedback into improved into rational design for improved lifetime - Improving the longevity/robustness of solid oxide fuel cells (tolerance to fuel impurities) - Ion transport in materials: dynamics, interfaces and structure - Electrocatalytic materials: stable; earth abundant or renewable; good catalysts - Rational design (e.g. simulations) of electrochemistry and architecture/morphology of sustainable energy storage systems (e.g. materials and lifetime) - Non-precious metal catalysts for polymer fuel cells - Finding alternatives to critical materials (e.g. platinum group metals – PGMS; rare earths for batteries; fuel cells; permanent magnets etc.)
Hydrogen and other forms of storage	11. Implementing hydrogen as a sustainable energy vector	- Electrolysis of unpurified water at natural pH - Higher temperature electrolysers – materials and systems to improve rate of oxygen evolution reaction and find a use for oxygen produced - Sustainable hydrogen production: electrolysis (PV, wind); photocatalytic water-splitting; artificial photosynthesis; photosynthesis - How can we produce low-cost green hydrogen for energy storage and mobile applications - Need high capacity energy store for vehicles (e.g. 9% weight hydrogen store) - Hydrogen feed into natural gas grid. Does hydrogen embrittlement of pipe system, need research? - Massive/long-term hydrogen storage in geology/mines over seasons/years/decades for security in an uncertain future (e.g. climate change) - Making fuel using algae
	12. Capacitive storage	- Loss-less capacitors for short- and medium-term charge storage - Hybrid device ("supercapacitory" lithium-capacitor) - Fast charge-discharge - Develop vastly improved supercapacitors for power control, transport
	15. Thermal storage	- Low cost thermal storage using cheap, perhaps natural, materials for all grades of heat according to application (but carnot-efficiency limitations) - Improved materials for thermal energy store e- hot and cold – long-term strategic research

7.3 Key points

The following key points are derived from the feedback that each community gave to plenary. The specific invitation was to highlight the 'buried treasure' that they had uncovered. The detailed outcomes of the work of the four communities are summarised in sections 7.4-7.7. Annex B contains a detailed record of discussions.

General and research process

- Long term investment in research is needed for continuity and for the UK to compete internationally.
- 20 year research programmes with strategic review?
- Need consistency of funding.
- Research should be a-political.
- Critical mass is key to successful research – bring communities together including industry
- Need a national database for new materials with guidelines for evaluation. Which materials raise which issues?
- Need a strategic framework to establish challenges.
- Need frameworks that enable simpler and more effective collaboration

Infrastructure

- Need investment in tools and infrastructure: computational and experimental tools and techniques.
- STFC has world class facilities which need to be maintained.
  - Maintain and increase availability.
  - Stop worrying about marginal cost given large up-front costs
  - As industrial challenges get harder (e.g. smaller scale), they will need to use these facilities increasingly.

Industry links

- Need to link with industry for transformative technological solutions.
- Needs strong engagement to overcome reluctance of the building industry.
- Need to link battery and built environment communities.
- Exploit knowledge from systems implemented in the field and feed this back into materials research.

Specific science and technology challenges

- Electrochemical storage will dominate transport as well as domestic and industry scale. Lithium-air technology has huge potential but faces major research challenges.
- Materials for application in electrochemical devices
- Fail-safe aqueous batteries.
- Storage targets need to be revisited and compared across technologies. Cost, environment, toxicity and sustainability matter as well as capacity.
- Need storage on different time-scales (hourly – seasonal).
  - Combined PV and storage is crucial for the medium term.
  - Multi-functionality such as building integrated PV, offsets cost and adds value for business.

7.4 PV

7.4.1 Cluster 3: PV and hybrid system integration

- Building Integrated PV disruptive?
- Durability (40-60 years) – aging tests?
- New materials
- Low cost: half current cost; material/processing/system integration
- High enough efficiency: power per area; C-Si 20-25% on roofs
- LCA, sustainable

- Multi-functional: alternative materials with flexible efficiency targets; shading, cooling, colour, structural, aesthetic appeal
- PV with storage: delivery ~6 hours (day night) immediate
- Transformative storage for all renewables, scalable and local: ideas immediate; seasonal delivery and design 2030; implementation 2050
- Integration of heat and PV: reduce installed costs by 10% immediate; integrate with building design and regulations 2030; smart buildings 2050
- National metrology, management and modelling: PV specific modelling and metrology; leading top system optimisation and control immediate; policy instruments and implementation 2030
- System quality assurance and due diligence: risk assessment immediate; quality assurance /production 2030

7.4.2 Cluster 6: Materials for new PV devices

Ideal material properties for Building Integrated PV (BIPV):

- Non-toxic
- Earth-abundant
- Stable
- Recyclable
- Available
- Appealing, e.g. choice of colour
- Low-cost manufacture
- Potential for high efficiency (20-25%)
- Appropriate for building use
- Life cycle assessment – high energy yield

7.4.3 Cluster 7: PV modules and manufacturability

- Immediate-medium term: achieving high efficiency; maintaining efficiency in scale-up; high volume/lost-cost manufacturing; develop test methodologies for durability
- Medium to long-term: Test for durability after 40-60 years in the field
- Immediate: UK repository of standard testing protocols and results for new materials
- Medium-term: validation of theoretical work from testing repository to predict limits on materials
- Long-term: development of disruptive new materials selected through validation
- Undetermined timescale: spatial measurements on operating devices; engineering optical and electrical devices
- High efficiency module architectures : 12% immediate; 20% 2030; 25% 2050
- Durability: 25 years immediate; 40-60 years 2050
- Appropriate functionality: global market analysis immediate; products for retrofit and new build 2030

Other research challenges:

- Novel architectures, e.g. interconnection, encapsulation
- No wires?
- Optical management within module
- Understand cell to module cooling losses
- Reduce losses by 50%

- Aesthetics
- Engage with construction, architects and planners
- Installability
- Manufacturing on large scale
- Process monitoring
- Rapidly scalable manufacturing processes
- Tools metrology
- Reduce production time by 50%

7.4.4 To address these, what do we need in place?

Economic/political

- Incentives for industrial engagement with R&D
- Incentives for long-termism
- Support for engagement with construction and design industry
- Longer term (2o0 year research programmes (with strategic review) focused on 2050 targets
- Mechanisms for effective networking

Co-ordination and national needs

- PhDs linked to industry
- Interdisciplinary PhDs
- MSc level programmes in the field

Infrastructure

- Mechanisms for world class laboratories and test/demonstration facilities

7.5 Battery storage and distributed energy systems

7.5.1 Cluster 4 Distributed energy systems

- Engineering/power electronics
- Consumer/industry led
- Low cost domestic energy storage
- DC house
- Hybrid generation/storage
- Buildings as power stations
- Vehicles to grid
- Solar thermal
- Structural batteries

7.5.2 Cluster 10 Future lithium-air and metal-air batteries

Lithium-air – beyond sodium-air etc, metal-air alternatives, mechanistic studies)

- Electrolyte stability
- Electrode structure, optimise porosity
- Oxygen solubility to increase power density
- Gas membrane oxygen in/out, everything else blocked; open/closed
- Stable interfaces

- Membrane electrode assembly
- "anodes" - is lithium suitable?
- Solid electrolytes
- electrocatalysis

Lithium-ion and sodium-ion

- Safety
- Electrolytes – liquid/solid
- Remote monitoring= soh/soC (?) battery management systems
- Nano-ionics
- Power
- Aqueous batteries/domestic environment/distributed energy systems
- Anodes – silicon/tin/carbon
- Lifetime – stability/passivation layer
- Electrode interface
- Electrode architectures
- Transfer to automobiles/stationary
- Cathodes – silicates/poly-oxy anions

7.5.3 To address these what do we need in place?

Distributed energy systems

- Retrofitting legislation/costs to frame best practice as in Germany
- Training electrochemists
- More interaction with built environment people
- "Green house" – lots of demonstrations and technology evaluation

Batteries

- EPSRC grand challenge calls
- EPSRC calls for 5+ years with CASE studentships
- STFC facilities for computational applications

7.6 Materials and other storage approaches

7.6.1 Cluster 8 Other storage approaches

Immediate

- Find efficient use for oxygen released during electrolysis to make hydrogen
- New ceramic materials for hydrogen oxygen, CO_2 separation

Medium-term

- Electrocatalysis for CO_2 conversion by electrolysis
- Electrocatalytic materials for CO_2 electrolysis
- Stable gas separation membranes /porous structures
- Low temperature CO_2 electrolysis (polymer systems]. Efficient electrodes
- High temperature CO_2 electrolysis, efficient electrodes

- Microbial systems for electrolysis systems
- Syngas production by CO electrolysis
- Reversible fuel cell/electrolyser
- Molten salts as storage vector
- Electrochemical synthesis of fuels using excess electrical capacity (over and above hydrogen)
- Improved thermo-electric materials

Long-term

- Develop high capacity low loss electrochemical capacitors for short term load levelling
- Understand factors limiting performance and life for high temperature electrolysis (water,CO_2, air)
- Novel materials and devices for solar fuels, photocatalysts etc
- Other electrochemical phenomena as storage: electrocapillarity streaming (?) potentials, electro-osmosis etc
- Using/consuming CO_2 in energy cycle/as vector
- Solar furnace redox CO_2 to CH_3 OH to produce fuel form CO_2
- Electrolytes
- /electrolysis for other elements oxygen "batteries" storage ($Al3+$, $Mg3+$)
- Large scale batteries for buffering intermittent wind/tidal
- Improved ionic/mixed conducting membranes for gas separation
- Advanced manufacturing (e.g. 3D printing_ for electrodes/membranes
- Linking CO_2 electrolysis to renewables (+ carbon capture from power stations/recycling fuel)

7.6.2 Cluster 9 Fundamental understanding of materials and interfaces

Immediate

- Deep understanding of all loss processes within PEM fuel cell catalyst layers
- Better oxygen reduction/evolution (ORR/OER) catalysts for acid fuel cells and electrolysis (i.e. least over-potential)
- Alternative catalyst supports to carbon for PEM fuel cells to avoid corrosion and degradation
- Focus electrochemical device work on materials and systems that have a good chance of increasing efficiency of conversion
- Should we be focusing on H^+ polymers or OH^- polymers?
- for lower temperature operation of solid-oxide fuel cells there is a need for more efficient cathodes
- Accelerated aging of fuel cell/battery materials
- PEM fuel cell membranes that are much less sensitive to hydration/de-hydration
- Understanding/mitigating SEI (Solid Electrode Interface) formation

Medium-term

- New materials and chemistries of flow batteries – low cost, long life
- A need for an efficient "dirty" fuel (e.g. S in natural gas) anode for solid oxide fuel cells
- Higher energy density batteries need safer electrolytes
- An efficient all solid state lithium ion battery for improved safety (issues with improving electrolytes and interfaces)
- High capacity lithium ion battery anode (silicon, tin)

- Understanding dendritic growth in operating batteries
- Replace precious metal catalysts
- Non-nickel electrodes for solid oxide fuel cells
- Safer large scale lithium ion batteries (non-lithium, carbon and oxygen)
- Recovery of lithium ion battery components
- The development of a truly reversible efficient SOFC/SOEC (solid oxide fuel cells/solid oxide electrolysis cells) system

Long-term

- Can we design fuel cell materials to allow operation between 200-500 degrees? New electrolytes required
- A good description of electrode/electrolyte interface (lithium battery)
- Efficient magnesium ion batteries
- Optimising/understanding grain boundaries in ionic conductors
- “in-silico” testing of electrochemical devices
- Computational modelling of real nano-structural electrodes: kinetic maps transport, structure

Underpinning

- Imaging/spectroscopy of material degradation now!
- Bridging the gap DFT/MD -> continuum understanding of materials
- Development of in-situ characterisation tools
- Model validation
- Techniques/measurement that handle disorder, real-world materials
- Computer simulation to become genuinely predictive of properties /reactivities
- Can we solve the limitations of modelling (e.g. underestimates, cation diffusion/interfacial reactions)
- Characterising the device(tools for looking at the materials in-situ)
- Integration of structural and properties measurements – towards predicted Quality Factors
- Access fast timescale information to study processes, e.g. sorption, band formation
- New experimental tools to investigate materials under operating condition for electrochemical devise
- New methods to characterise materials beyond the unit cell
- Understanding mechanisms of materials degradation in electrochemical energy storage devices
- Understanding mechanisms of degradation in fuel cell devices
- New computational tools to design and prepare materials with a focus on surfaces and interfaces for electrochemical devices
- Electrochemical devices: linking materials design to process/fabrication routes – design characteristics at device level
- Understanding factors related to degradation to develop accelerated testing for materials and device development
- New membranes/ionic conductors for fuel cells and batteries – new designs/temperatures
- Techniques to separate ionic and electrolytic conduction in electrochemical devices
- Much more conductive PEM fuel cell membranes to reduce ohmic losses – high efficiency
- New solid oxide fuel cell oxygen ion conductors that work well at lower temperatures

- Stable alkaline (OH) membranes for low temperature fuel cells to allow non-platinum group metal (PGM) catalysts
- Recycling of high value materials from electrochemical devices – e.g. by developing process routes
- Quality factors to define new materials
- Long-term lifetime testing/analysis of solid oxide fuel cells
- How do interfaces change over time in a solid oxide fuel cell? What is the effect of long-term cation diffusion?
- What are the key degradation issues under operation in solid oxide fuel cells

7.6.3 To address these what do we need in place?

- Needs to provide benefit to UK companies and jobs (including new companies) as part of impact
- Better support for UK universities to take part in EU process
- World class experimental an computational facuilitie4s
- Engagement between academic community and broad range of industry stakeholders
- Capacity in the research base with critical mass in key area and disciplines
- Retention and access to STFC facilities
- Long-term challenges need long-term approaches
- Long-term frameworks to support collaboration
- Need to have sufficient scale to allow all the necessary disciplines to work together
- Need critical mass and long-term investment
- Strategy and coordination is needed to focus on electrochemical energy technologies
- Set balance between long-term/shorter term technologies, tools, techniques etc.
- Strategy in place and facilities available to the community
- Capacity in academia to do the research, capacity in industry to engage with and receive the research
- Collaboration frameworks need to be in place

7.7 Hydrogen and other forms of storage

7.7.1 Cluster 11 Implementing hydrogen as a sustainable energy vector

- Work with not against other storage technologies – added value assessment (hybrid etc.)
- Eliminate platinum group metals (PMG) from fuel cells
- Fuel flexible anodes
- Balance Of Plant reduction
- Biomass process learning
- Electrochemical utilisation of low-grade heat
- Complete revision of storage targets beyond US DoE
- Hydrogen storage – upgrade targets to include sustainability and recycling, e.g. solid state stores
- Hydrogen storage – modular/replaceable hydrogen tanks in vehicles
- Hydrogen storage agreed balance plant   volumes/????? For system capacity calculations
- Hydrogen storage –
- Molecular modelling and simulation of physical and chemical storage media
- Hydrogen – "green" hydrogen; alternative stores (?????)
- Hydrogen storage – molecular design of solid-state storage materials
- Hydrogen storage – integrate solid-state high-pressure gas tanks

- Hydrogen storage – assessment of storage across energy power and time scales – seconds to 10^8 seconds
- Long-life fuel cell
- Cathode improvement
- Thermal integration
- Power-to-gas

7.7.2 Cluster 12 Capacitive storage

- Design super-capacitors to work with fuel cells
- Increase temperature range of supercaps
- Manufacturability of supercaps
- Fundamental understanding of electrode surfaces
- Materials to achieve high energy capacity (> 200 Wh/kg) chemistry (electrode and electrolyte)
- New electrochemically stable electrolytes
- Asymmetric supercaps

7.7.3 Cluster 15 Thermal storage

- Condense size of thermal stores
- Low temperature, light weight storage
- High temperature storage
- Cryogenic storage efficiency

7.7.4 To address these what do we need in place?

- A blend of established track records and opportunity for truly innovative youth
- Truly open competition for funding but targeted calls
- More sifting/pre-bids at RCUK level (more efficient bidding process)
- Improved and coordinated networking opportunities
- The question does not allow for serendipity – unexpected advances from a firm basis in fundamental science
- Those best able to do such research may not have PhD studentships available for associated training
- A balance which permits long-term research objectivity and flexibility in virement and duration
- Research training at truly active research centres executing funded research programmes
- Energy-only responsive node
- De-politicise all research funding – good science does not depend on left or right
- Economics – new technology is always expensive, much look beyond long-term
- The UK must invest in long-term significant funding to match international competitors
- Sustainable (and career-path directed) development of researchers from undergrad to professor
- Ensure sufficient and flexible research space (public/private sector)
- Work in series – co-research development with industry
- Challenge current metrics for measuring research performance
- Is current RCUK process for securing research funding fit for purpose
- Challenge the concepts of inter- multi-disciplinary research – what does this mean?
- Need long-term continuity (> 5 years, 10-30 years)
- Clear pathway up TRL chain
- Better engagement with policymakers, the public, multi-media (good PR)

8 Research Cluster 'Deep-Dive' 2: Community Cross-Cutting

8.1 Methodology

Participants were allocated to five groups. Participants were allocated to the groups with a view to mixing up the communities that had carried out the "deep dives" described in Section 7 were mixed. The groups were assigned the remaining clusters/super-clusters as shown in Table 4.

Table 4: Allocation of Cross-cutting clusters

Group	Selected Clusters/Super-Clusters	
	No.	Description
A	2	Sustainability issues
B	9	Fundamental understanding of materials and interfaces leading to new improved materials (lower cost, abundant, better performance)
C	14	User behaviour and demand
D	5	Hybrid systems
E	13	Issues of scale

To assist the deep-dive process, each team was provided with an activity sheet with a set of questions and suggestions as to how each question could be approached. The questions were as follows:

1. What are the main research challenges we need to address for our research to be first class in terms of both excellence and impact? Although participants were asked to consider immediate/medium term (2030)/ long term (2050) needs, in practice this did not prove possible.
2. To address these challenges what would you like to see change? For example consider:
   a. What needs to happen in terms of coordination and alignment to maximise success in your research area?
   b. What do we need to have in place to ensure we are ready to address these research challenges (e.g. PhD training, data collection/curation, research Infrastructure, funding philosophy etc.)?

Participants were asked to agree three points from their discussions that they felt must be included in the report and to move to another table group half-way through the session in order to ensure that all participants were able to discuss their research clusters of interest.

The groups reported back their key outputs in plenary. These key outputs are recorded in section 8.2. These have been edited to avoid repetition.

8.2 Results

Group A: Sustainability Issues (Cluster 2)

- **Scalable, low-cost thin film deposition methods**
  Thin-film deposition methods are important to many electrochemical technologies – methods of cheaply producing high-quality, low-cost depositions at large scales would help deployment efforts immensely. Process engineers would be important to this process.
- **Removing and recycling scarce critical materials from products**

Many designs of fuel-cells, batteries and solar PV cells use rare-earth minerals and other rare materials, which are in great and increasing demand. Products could be designed to make removal and recycling of these materials easier and cheaper, and methods of recycling these materials should be designed to be cheaper and more efficient. Can researchers design technologies which can use other, cheaper materials in place?

- **Total embedded energy in a device – ways to measure and understand it.**
  Researching methods to measure the embedded energy and carbon emissions in a device, and identifying possible ways to reduce lifecycle emissions and energy costs.
- **Degradation issues – improve lifetime of device**
  Electrochemical technologies such as batteries often have problems with degrading over time, meaning that they often degrade before other components in the device. Improving the working lifetime of electrochemical technologies should be seen as a priority

Group B: Fundamental understanding of materials (Cluster 9)

- **Friendly, user-accessible fast computers**
  Materials research requires complex molecular modelling and simulations. These would be best handled by fast, powerful and cheap computers, which could be user-friendly to allow non-experts in computing to access these models and research.
- **Validation of models and simulations using shared lab facilities**
  Materials research requires complex molecular modelling and simulations. These would be best handled by fast, powerful and cheap computers, which could be user-friendly to allow non-experts in computing to access these models and research.
- **Application/demonstration of models – handing over to industry**
  There needs to be more joint or joined-up research with industry in this area – closer collaboration, including the handing over of models to industry, could accelerate the development of new materials in commercial products.
- **Methods to measure the performance of the device while in operation**
  Materials and interfaces may exhibit properties in the lab which interact in unforeseen ways when used in an operating device. It would be useful to further develop methods to measure the performance of these materials/interfaces when in an operating device, and how they may affect the performance of the overall device.
- **Reproducibility – need to be able to reproduce results**
  Materials and interfaces need to show a high degree of reproducibility in order to be used in functional devices. Experiments need to be checkable and reproducible. It was suggested that there could be an incentive scheme to check published results in order to ensure regular and rigorous checking of published findings.
- **Sharing of expertise and facilities and equipment**
  This sector benefits from large, well-funded test facilities and equipment. In addition, greater sharing of expertise will prevent duplication of effort.

Group C: User behaviour and demand (Cluster 14)

- **Interdisicplinarity between social and technical scientists**
  Social science is extremely important in this area for understanding how people use and interact with electrochemical devices and storage. To design products to best fit customer needs, engineers should be able to understand general principles of social science and social science language, and social scientists should be able to understand what is possible in engineering and producing devices.
- **Demand-side management – understand social aspects**

There is a need for psychological research into what is actually effective in incentivising people to adopt demand-side management - effectively incentivising behaviour change. Researchers and developers should survey and understand what has been accomplished in this space, and how this work could be translated into effective policy mechanisms and successful devices.

- **Political support and long-term ism. Policy tools to enable demand side management**
  To incentivise developers and suppliers to invest in these technologies, there needs to be strong policy support tools, as well as a shift to 'long-term' thinking, where support is guaranteed for a number of years.
- **Research into effective incentives and barriers to DSM solutions**
  Are smart meters currently visible enough to their users? Visibility and awareness is key to changing behaviour. Sunshine and solar PV is an easier connection to make, but still important. Researchers need to understand the early adopters in this area and their motivations – early adopters can often help increase deployment.
- **Public education – what is energy storage and what can it do?**
  The general public currently have a very poor idea what the grid is and how it works. Educating the public, perhaps through long-term methods, on what energy storage is, why it is useful and how it could reduce CO_2 emissions could greatly aid policy and deployment efforts.
- **Understanding attitudes to asset ownership**
  Attitudes to asset ownership, particularly in urban areas, appear to be changing. For instance, people are often signing up to car clubs instead of owning their own car in cities, due to the cost of parking and maintenance. This could be very useful for electric vehicles, for example, as the cost of battery replacement would be borne by the hire company, not the user directly. Understanding these changing attitudes will help inform future research and development in storage and community energy.

Group D: Hybrid Systems (Cluster 5)

- **Modelling to understand how best to integrate hybrid systems.**
  How can you model decoupled hybrids (e.g offshore wind, onshore storage) in terms of optimal placement and distance? Models are needed to determine how hybrid systems integrate into the national grid, and what measures will have to be taken.
- **How could system efficiency be improved, and improve separate parts of the hybrid to be as durable as each other?**
  Researchers should consider hybrid systems as they design new systems and materials. Are multifunctional materials the answer if one of the functions of the hybrid is suboptimal or not competitive?
- **Algorithms for control and system integration.**
  Smart control systems and getting components to communicate properly is crucial for hybrids. Control systems and algorithms for maximum fuel efficiency is an important topic, as well as optimisation of micro-generation/storage hybrid systems.
- **Hybrid test facilities.**
  Demonstrator test-beds need to be in place to test the complexities and different configurations introduced by hybrid systems. Hybrid systems also have complex interactions with the electricity system – facilities need to be able to test these as well.
- **Partnership between academia and industry – knowledge sharing**
  Knowledge of the potential applications of hybridised systems is needed very early in the process. Industry needs to be engaged very early to maximise success. Is there a way to increase mobility of academics and industrialists between academia and industry to form new equilibria and improve knowledge sharing?
- **Need more active engagement from DECC and BIS.**

DECC and BIS should be more engaged with the direction of research challenges, as they are charged running and evolving the energy system.

Group E: Issues of scale (Cluster 13)

- **Long term strategic road-mapping**
  World-class battery development nations like Japan have a system of long-term road-mapping of development, coupled with long-term funding from companies. The UK in order to compete at large scale should concentrate on producing strategic roadmaps for electrochemical technologies, focusing on how academic research and industry can collaborate and how the UK can best utilise its distinctive strengths.
- **World-class test facilities**
  Scientific, prototyping and large-scale testing facilities are crucial to scaling up technologies from laboratory to commercial scale. This is an underfunded step in the UK's research capabilities. There is a need for large-scale demonstrator sites as well, which are often difficult to organise in the UK.
- **Increased capacity in academia and industry to deploy new technologies.**
  There needs to be stronger links from industry to the academic scientific base, and new methods of streamlining the demonstration and commercialisation of new research.
- **Supply chain for materials**
  The UK should look for opportunities where it can contribute to the global material supply chain. Is all the value in a technology such as a battery in assembly, or could the UK add value by contributing specialist materials to the process? The UK could compete more in advanced manufacturing than assembly, especially if the manufacturing capabilities are flexible.

9 Reflective Writing

9.1 Process

The purpose of this exercise was to provide participants with the opportunity to build upon ideas they had formulated during the clustering and deep-dive exercises and allow them to flag any broader issues they wanted to raise.

Please note that after the workshop invitees were provided with a draft copy of the workshop report, which they were encouraged to provide feedback on. Any feedback provided by invitees is marked with an * to identify it as a post-workshop reflection.

Option One: *Chat Room*

A room was provided for participants who wanted to talk through their reactions to the themes and research ideas. In practice this tool the form of a walk in the gardens. A note taker was present to record the discussions.

Option Two: *Reflect and Chat*

Participants in this room first reflected individually and subsequently joined together in groups of three to discuss their individual reflections. This enabled participants to develop their ideas by 'bouncing' them off other members in their group.

No-one selected a third option for individual reflection. Participants were also encouraged to post any written output from this session into a reflections post box or email their thoughts to the organisers.

9.2 Chat room output

Insufficient coverage of fuel cells. This was possibly since people did not consider fuel cells to be a storage technology and had perhaps misunderstood the workshop title.

- Why had PV had more attention than fuel cells?
- Hydrogen had got some attention and vocal support within the group – maybe fuel cells had no vocal champion.
- Notably, there had been no fuel cells cluster, even though UK industry works on this technology and there are good opportunities for exploiting research.
- There is still lots still to do on fuel cells, lots of good people and good infrastructure for research.

Cutting edge results. No-one had spoken about the most cutting edge research results.

- How far have we got with different technologies?
- What are the feasible goals for performance?
- How significant are individual technologies
- Should we focus more on potentially breakthrough technologies (super-capacitors?)

Material science perspective. There are lots of different agendas within this group. This makes it difficult to compare technologies as people tend to fight for their own.

- LCAs are done differently by everyone
- Need to understand quality factors (i.e. how much better do you need you make your material and in respect of which properties?)

9.3 Reflect and chat output

This sub-section is based on outputs deposited in the reflections post-box. Comments are grouped into the following themes: research focus; research funding and process; training and capacity; international; industrial and other links; and the workshop itself.

Research Focus

- All must be based on fundamental physical and chemical science knowledge and understanding of materials and processes.
- How to facilitate adventurous energy storage research.
- Most suggested research challenges addressed immediate (possibly incremental) issues. Needed more discussion on transformative, long-term possibilities. Was this inherent in the tasks?
- Electrochemical theme lost in many discussions – needed re-iterating
- Research into hybrid/combined technologies
- Combined PV generation with storage could be transformative in connecting large amounts of renewable energy top the grid.
- Future energy storage will encompass many different technologies – thermal, electric, chemical, kinetic gravitational. These have different performance and application areas and must be selected individually, or in a collection for maximum system performance.
- Low/non-rare earth permanent magnets for motors.
- Super-conductor energy storage
- Storage solutions to match electricity generation profile.
- Novel architectures and devices optical design

- Missing emphasis – cost-benefit analysis of research options. Mechanical and SMES technologies were not represented. However, these would be expensive to research and could squeeze out other research themes.
- * there are recurrent themes that would mean a change in research landscape and a lot of these are in relation to linking of technologies such as hybrid systems, durability, integration with building materials and the building envelope.

Research funding and process

- Consensus: research goals; research breadth (including adventurous); consistent funding; need for interfaces with industry/government…
  …need: grand challenge; consistent funding; performance feedback for materials design; more collaborative, less competitive research approach; identify overlap, don't swamp subject sin clusters; mix of targeted and fundamental research (too tilted towards targeted at the moment); critical materials evaluation
- Separation/joining of science and engineering.
- Greater coordination and cooperation across the UK research community is needed. This needs to be rewarded with long-term research funding.
- Critical mass is essential to allow full range of disciplines to engage.
- While critical mass is important, need also to ensure a diverse research base.
- Non-inclusive approach to research funding limits progress, e.g. SUPERGEN hubs. Academics not in original consortium frozen out.
- If funding stays with "the usual suspects" it will breed cynicism in the community could hinder original and possible transformative thinking.
- Long-term funding
- How does this all fit with current Research Council and other funding structures – should there be an energy innovation programme incorporating EPSRC, BBSRC, NERC, STFC, TSB, DECC?
- "Pathways to impact" does not adequately address public engagement – we need other mechanisms

Training and capacity

- More attention to training
- Co-ordinated and strategic research career development: PhD to Professor
- Investment needed over long-tern in people (capacity) and appropriate equipment and staff to operate it. This is relevant to the electrochemical challenge.
- Need independent research/technology facilities to provide area/centre of expertise to access.

International

- Has someone compared strategies in this area with comparable countries – Germany, France etc.?
- Is the UK taking advantage of international networking opportunities?

Industrial and other links

- Need coherent national level plan to implement technologies – with determination to meet targets as a framework within which research effort is undertaken.
- Partnership between disciplines and with industry is essential. Simple mechanisms are needed.
- Engagement with industry and user community is essential in developing the research landscape. Common understanding and ownership of research themes.

- Need more industrial perspective from established companies based in the UK (both UK-domiciled and multinational). Industry has been "other" during the workshop.
- Must aspire to better and sustained engagement between academe and industry, the public, policymakers…nationally and internationally.
- Easy mechanism for working with industry – Scottish "Energy Technology Partnership" PhD studentships a good example

The Workshop

- Electrochemical science in energy is key. The general discussion added less value.
- PV well represented, other technology communities not.
- A lot of time wasted on generalities – research has to be on specific topics
- No really novel systems proposed – new battery chemistry.
- Impressed at the consensus between different expert group son the big challenges
- Could have been spread over 1½ days not 2.
- Disappointed with lack of participation by government, policy and industry to provide feedback on what is realistic and what they would support.
- How will the output be used and what influence will it have?

10 Key pointers for the Research Councils – start/stop/continue

Participants worked in groups of three in order to identify activities that the Research Councils could either:

- Start doing/do more of
- Continue to do
- Stop doing/do less

The responses were recorded on flipcharts and each group reported back verbally on one issue they had identified. Table 5 below presents the outputs of this exercise. There was a clear preponderance of requests for the Research Councils to prevent 'siloing' of research and to encourage interdisciplinary collaborations and collaborations with industry. There was also a desire to move away from the focus on CDTs for PhD training purposes into more grant- supported PhD students. The desire for a clear shared vision, strategic themes and cross-Council programmes were clearly signalled.

Table 5: Suggested Actions for the Research Councils

Start doing/do more of	Continue to do	Stop doing/do less
	Research Focus	
More risky/blue-sky research	Continue to fund blue skies research (will lead to transformative technologies)	Treating H_2 separately from storage.
Make electrochemistry and electrochemical engineering a priority area.	Ionic liquid (molten salt) based electrochemical conversion and storage.	Fuel cells, CCS (but continue CCC)
Start to link funding to bigger picture/2050 goals.	Redox flow batteries (more stable membranes, less corrosive electrolytes, improved kinetics).	Step changes in components and materials.
Grand challenges on Li-ion batteries		Stop CCS research
Supercapacitor and battery hybrids – device structure design, material design		

& R+D.		
Electrochemical conversion between low-grade heat and electricity.		
More system and device focussed studies.		

Start doing/do more of	Continue to do	Stop doing/do less
Research style		
Developing sustained long-term programmes	Continue to value peer review & transparency.	Stop chopping and changing
Consider long-term funding – including challenge areas in experimental & computational tools for the field.	Continue grand challenges.	
Fund more incremental applied science with potential for large impact	Support 5YR+ fellowships in key research areas	
Enable longer-term integrated research towards transformative technologies.		
More international engagement (EU+USA)		
More strategic approach to managed calls.		
Interdisciplinary research on comparing benchmarking of new technology.		
More long-term research programmes (10 years).		
PhD Training		
'light-touch' responsive mode	Continue responsive mode funding + PhD training	Unrealistically short deadlines
Must be able to fund PhD students outside of CDTs in this field.	Continue with responsive mode calls – include RM in energy programme.	Only apply 'demand management' penalty to unfundable grant proposals.
More inclusivity e.g Supergen hub+spoke	Continue fellowships at all 3 levels but less prescriptive.	DTCs
Having a more coherent approach with other funders.	Continue to allocate industrial CASE awards (for industry to allocate to chosen university).	CDTs
Cross-council cooperation.		Reduce emphasis on CDTs
Start consulting with industry on research topics for this area.		Stop constraining equipment purchase.
Only have a call for proposals if there are funds to give a reasonable success rate.		DTCs
Allow studentships on grants.		
Support European PhD students		
Allow PhD students on grants		
Makre sure panel members have sufficient expertise, including having international independent experts.		
More active monitoring of milestones esp for big programmes.		
Other		
More central facilities	Continue to maintain world-class STFC facilities and make access available.	

11 Wrap-up and next steps

On behalf of the Fellowship team, Jim Skea summarised the next steps.

- A draft summary of the workshop proceedings and outputs would be circulated to participants within one month.
- There would then be an opportunity for participants to comment on/add to the report. This would then be posted on the Fellowship website.
- The record of the workshop would form the primary source for the peer-reviewed electrochemical energy and storage research and training prospectus to be produced over the summer. This would also be web-published.

Annex A – Key Questions Being Addressed Around Electrochemical Energy Technologies and Energy Storage

Table 1

- Molecular science of hydrogen containment, phase behaviour, integrating solid state hydrogen storage into state in the art 70mpa, improve operation or if good idea at all, is it worth looking at integration of all energy storage systems
- Dual use of batteries between vehicles and grid, can you use it to supply the grid? Optimisation of hybridisation, combustion engine has a long way to go, can we optimise it along with other techs Cost and how to control those systems How can you accelerate degradation testing
- Interaction of materials chemistry and devices. Cost, stability etc. Interaction between two, novel materials, working together in harmony
- Material scientist, interested in high density energy storage, new materials for storing hydrogen and electricity for batteries, integration of batteries for grid and transport. Importance of strategic materials
- Materials scientist, ceramic conductors, fuel cells now batteries, safety and performance, ceramic electrolytes and electrodes. Fuel cell and electrolysers, photo conductor membranes
- Biologist. Generation of electricity is easy, storage is a problem. For long term storage, chemical bonds are best. Hydrogen would be one way, but there are others. Can we learn from microbes, which can store energy in chemical bonds by growing in presence of electropotential – "geobacter".

Group Discussion

- Storage, materials, hybridisation
- Time scales - How much and how fast can charge, how long can store, and how long to deliver
- Cost and techno economics. Techs are not cheap when they are young. Fossil fuel subsidies – unfair comparison anyway. Need to invest to know if it can be cheaper.
- Process needs to push things right down the road to see if they will work.
- Can LCOE model the cost of wars and environmental damage, health? This has to be a political decision. Realistic sociotechnoeconomic modelling could make a more convincing case.
- Hybridisation is a way of introducing the economics. Introducing dual drive system into a car - this was expensive earlier but had support of Japanese government.
- Cost limited a lot by the lifetime, degradation, which we can't control.
- Timescales, decadal time.

Table 2

- Sustainable energy storage – find one which doesn't deplete something we're already short on, and for this to work on large scales (e.g. *all* cars) – material criticality.
- value of basic tech research vs. taking action. How to find solution to intermittency, public expectation, how our small projects fit into the big picture
- Big complicated issue, no one solution, but everyone wants their own piece of cake, too much competition, putting down competing technologies – how to work together
- Challenge is getting research out, how to get demand from the public (challenging since tech will be expensive), will government support one storage tech, Should we focus on only things which work in the UK

- Cryogenic energy storage (material processes, efficiency, costs), Business models for storage in industrial or campus scale, policy and market barriers to putting storage in the grid.
- Bigger, cheaper safer electrochemical storage solutions, at all scales and transport, how to compare tech, techno-economic drivers for storage.
- What is the ideal fuel? How can batteries which don't use rare materials be , reversibility of hydrogen storage needed?

Group Discussion

- Common challenge – storage: lifetime, sustainability (materials scarcity), cost, *value*, safety. Value more important than cost.
- People will refuse price increases without demand for new technology.
- Need to know where the markets will be in long term future – can we rely on linking grid to EU
- Policy uncertainty is big challenge for private sector. Certainty more important than subsidy.
- But payback on investment into start-ups is a challenge (since long time-frames) – so maybe subsidy is required in short term.
- We have public good attitude to storing back-up gas and petroleum, could similar model be applied to electricity storage.
- Should look at storage as a way to make RE cheaper through solving intermittency – but we have lots of gas which defeats this argument since is very flexible.
- Distributed storage will penetrate much easier into market (than centralised solutions) but only if people has access to electricity spot market, or at least variable cost over the day. Why not let people buy their own storage and help contribute to grid stabilisation – Already happening in storage being put into PV systems in Germany.
- Local, situation specific solutions. Sometimes, distributed storage (or distributed heating) works excellently but not always (e.g. in densely populated areas).
- District heating annoys people since they can't control it. Public expectations can make technologies inappropriate if these issues are not addressed.

- Availability of strategic materials in batteries and recycling
- Now using electrochemical storage in new ways – scaling up from consumer electronics to cars and buildings is challenging, need to select the likely
- Need stability and more imagination in storage policy.
- Don't put down other peoples technologies. All are complimentary and we should work together.

Table 3

- Why do you think you can make a fuel cell in uncontrolled conditions - need a more rational approach to materials.
- The efficient use of heat. Nuclear plant charging a thermal store - becomes a dispatchable form of energy.
- The interface of electrochemistry with lithium batteries - understanding the chemistry with spectroelectrochmeical techniques. Understanding the reaction mechanism of lithium batteries and how electrocatalysis works.
- Solid-oxide fuel cells operating at lower temperatures - how do you do this?
- My interests are in thin-film PV -integration and manufacturing. Developing a low-cost PV when silicon costs have fallen is very difficult. Integration of PV into buildings more effectively. Managing energy supply and demand. High cost of storage - many issues there.
- Thin-film PV - materials which are long-term and stable. Thinking about systems and how they are applied. Solar being the largest and most well-distributed energy source- important to take advantage.
- Solid oxide fuel cells and batteries - difficulty for single institution to devise. Difficulty with access to small funding levels for projects e.g PhD students.

Group Discussion

- Lifetime is crucial in almost everything. Sustainability and availability of materials. Needs to be price-competitive. Integration of photovoltaics.
- Attractiveness. people don't like things that look ugly.
- Building costs are a large part of the cost of any system. Integrated system - needs to have a lifetime of over 20 years to be transformative.
- Inverters and power electronics now getting better and coming with 25-year guarantees.
- Batteries for Nissan Leaf guaranteed for 7 years - they lose money on this. Do we worry too much about designing better batteries - maybe design better cars? Very hard to find useful data on these relationships.
- Durability is important - do we need a set of UK benchmarks?
- Should the Research Councils adopt US/EU benchmarks for projects to define lifetime/durability for research?
- Need a consistent, continuous target strategy for the UK - comprehensive strategy - almost need to be on a wartime footing.
- We only put 1.4% of GDP in the UK into funding - the US, for instance, spends 2.4%.

Annex B – Detailed Outcomes of Research Cluster Community 'Deep-Dive'

Group 1: PV

This group chose to address Question 1, "What are the main research challenges we need to address for our research to be first class in terms of both excellence and impact", for all three clusters under consideration, and then address question 2, "to address these research challenges what do we need in place", in a cross-cutting fashion

Question 1: What are the main research challenges we need to address for our research to be first class in terms of both excellence and impact?

Cluster 3 – PV and hybrid system integration

- Integrating PV with storage (hourly/daily shift)
    - Immediate –medium term: design and implement systems able to deliver shift of approx 6 hours
- Transformative storage for all renewables (Seasonal delivery)
    - Immediate: Ideas, early stage
    - Medium: Design and demonstration
    - Long-term: Implement

Integrating PV with heat

- Immediate: installation costs down by 10%
- Immediate-medium-term: Integrate with building industry to design and begin to implement zero or negative energy buildings at marginal extra cost to alternative
- Long-term: Smart buildings

- System out of a box (plug and play)
    - Immediate: Easy to install systems to reduce balance of systems costs
- National energy resource measurement, modelling and management
    - Immediate: specific modelling related to managing and controlling generation; system optimisation and control
    - Medium: Design of smart control technology to predict, measure and respond to changes in generation within the network
    - Immediate-medium: Policy instruments to implement the above
- System quality assurance and due diligence

Cluster 6 - Materials for PV devices

For this cluster, the group first defined the scope of their discussion. They believed that all innovation was incremental in the end. Integration with the grid is a challenge as well as improving the cost of modules etc.

- **Transition from bolt-on to buildings integrated PV.**
    - Multi functionality, shading, cooling, windows, sheet steel…
    - Marginal cost compared with what you're replacing
    - Low cost – half current cost?
    - High enough efficiency - c-Si 20%...25% by 2050?
    - New materials
    - Durability
    - LCA, sustainable materials

    - Designing for low-light efficiency
    - Ideal material properties (different applications will be more or less stringent for these):
    - High efficiency/high energy yield
    - Low cost manufacture
    - Energy yield/embedded energy high
    - Non-toxic
    - Earth abundant and available
    - Stable and durable
    - Recyclable
    - Appealing eg choice of colour
    - Appropriate for building use
- Efficiency and cost
    - Immediate-medium: better understanding of how to achieve high efficiency/what causes losses; maintaining efficiency at scale up
    - Immediate: Low cost manufacture; high volume production
- **Other research topics**
    - New materials screening
    - Spatial measurements on devices
    - Beyond the Shockley-Quiesser limit
    - Device engineering optical and electrical

Cluster 7 – PV Modules and manufacturability

- High efficiency module architectures (based on c-Si)
    - Immediate c-Si 12%+
    - Medium: c-Si 15%
    - Long-term: c-Si 25%
- Durability
    - Immediate: Power applications 25 years
    - Long-term: Power application up to 60 years (other applications less stringent)
- Appropriate functionality
    - Immediate: Market analysis for suitable applications where there is added value
    - Medium: New build or retrofit in niche areas; Radically new products with different module architectures
    - Long-term: Highly distributed solar power in many applications (embedded in environment)
- Novel architectures
- Interconnection
- Encapsulation
- Manufacturing innovation, particularly rapidly scalable pilot line to GW plant
    - Immediate: Identify manufacturing bottlenecks; tools for process monitoring and metrology
    - Medium: Reduce PV production time by 50%, reach 10 GWp
- Optical/light management in modules (not just devices)
    - Immediate: Having model to understand cell to module coupling
    - Medium: Using this, reduce losses by half
- Aesthetics
    - Immediate: Engage with building designers and architects
- Installability

Question 2: to address these research challenges what do we need in place?

- Economic/political factors
  - Incentives through policy for industrial engagement
  - Incentives for long termism in industry – for PV particularly building industry and architects
- Longer term (20 years) research programs – not unconditional, subject to eg 5 year reviews
- Training
  - More PhDs
  - Doctoral training should be linked to industry and interdisciplinary
  - Masters MSc level programs in field
  - All of these should be coordinated to meet national needs
- Infrastructure and equipment
  - National repository and forum for data sharing
- National testing platform (eg for PV)

Group 2: Battery storage and distributed energy systems

Cluster 4 Distributed energy systems

The Group believed this to be an industry-led challenge as it was all about engineering application type issues. The Group consisted of chemists and physicists and did not feel they had expertise in this topic.

Question 1: What are the main research challenges we need to address for our research to be first class in terms of both excellence and impact?

- Batteries with more flexible output - and more power - a research challenge,
- Low cost domestic energy storage
- Fuel cell CHP
- Vehicle- grid
- Monitoring state of health of batteries as challenge.
- Building integrated PV and sizing batteries appropriately.
- Batteries combined with supercapacitors for power pulses - don't ruin the batteries.
- Hybrid solutions
- Power electronics and battery integration.
- DC house
- Retrofitting? Legislation, cost barriers.

Question 2: to address these research challenges what do we need in place?

- Look at other countries eg Germany.
- Don't have enough electrochemists in the UK - dying breed.
- More interaction with built environment people. They just think batteries are black boxes. They do silly things, dry clothes, under the bed etc. 2-way process - need to understand how people will use batteries and design accordingly.
- Structural batteries (in walls) - therefore longevity will matter.

- Need demonstrators for all this stuff. Bigger scale needed. Evaluation. Need feedback into research prioritisation.
- Warwick catapult compared to Karlsruhe Fraunhofer is nothing. 300 PhDs in Karlsruhe. But devoted towards automotive sector. Automotive companies do research, utilities don't.
- Tata is interested in stationary storage.
- EERA (European Energy Research Alliance) can be used - need more of this.

Cluster 10 Lithium-air as the central focus

Question 1: What are the main research challenges we need to address for our research to be first class in terms of both excellence and impact?

- Electro catalysis - immediate, but less urgent
- Electrolyte stability - immediate
- "Anodes" is lithium suitable?
- Solid electrolytes - medium term
- Electrode structure - optimise porosity - medium term
- O2 solubility - increase power density -medium term
- Stable interfaces - immediate - avoid degradation
- Gas membrane o2 in/out - everything else (open/closed) - bring in industrial groups who know how to make membranes) - long term challenge but we need to start now. If not fixed, will be a bottleneck.
- Membrane electrode assembly (Companies want to do what they're doing anyway - eg cylindrical geometry)
- Scaling up
- Metal -air alternatives
- State of health/state of charge monitoring. Management strategies, remote monitoring.
- Discussion of US/UK capabilities - US pouring in Loadsa money, UK more focused and delivering research output.
- UK did the Li-air research but exploited elsewhere
- Have a consortium - eg SUPERGEN - which involves industrial suppliers - long term funding.
- Lithium - ion now (more mature - research structure is there) + sodium ion
- Cathodes - silicates. Poly-oxy anions
- Electrolytes
- Electrode architecture
- Nanoionics
- Anodes - silicon/ sn/carbon
- Lifetime - stability, passivisation
- Transfer to automotive/stationary. Energy density matters in some applications not others
- Safety of Li ion an issue.
- Other metals would lose energy density but there may be other benefits. Not as reactive. Energy density not primary criterion for every application.
- Zinc + aluminium have been studied. Not rechargeable hysteresis effects.
- Sodium and potassium superoxide have been demonstrated.
- Role of computational/theoretical sciences.

Question 2: to address these research challenges what do we need in place?

- We have the research capacity - needs support

- No capacity problem in testing also - facilities in place
- Catapult at Warwick has addressed a lot of problems
- Concerted programme needed
- Recent TSB grant call was written to exclude academics - not significant. Was a joint EPSRC-TSB call. Bad overlap between them. UK industry is receptive - will come to the meetings and interact- but won't commit real money. EPSRC's money was to top up and get academic input.
- Companies could act as catalyst.
- Call structure - EPSRC should have a grand challenge which could require industrial participation. (Thinking quite constrained by "what EPSRC does"). TSB not the right body (opinion). TSB needs to have technology close to market. TSB-EPSRC gap.
- Why don't companies put money in - they get the benefit.
- Iv) CASE student model to draw companies in.
- Universities don't have capacity - Fraunhofer style model for photonics in Scotland. Germans brought in to advise. Some people think good, but dangers of over-focus, lost training opportunities. Need to be 5+ years.
- Where's the bottleneck, senior people have too much to do. Longevity and vision needed.
- Lots of talk about admin effort.
- Data sharing not an issue. But groups don't share battery cycling data.
- IP will be an issue. First refusal for participating companies. The more you pay, the more IP you get.
- Won't get industrial interest for early stage research.
- Double jeopardy of STFC access
- Access to glove boxes, beam lines etc.
- Computational people find it hard to get responsive mode awards.
- Computational and experimental people should work in the same groups?

Group 3: Materials and other storage approaches

This group chose to address Question 1, "What are the main research challenges we need to address for our research to be first class in terms of both excellence and impact", for all three clusters under consideration, and then address question 2, "to address these research challenges what do we need in place", in a cross-cutting fashion

Question 1: What are the main research challenges we need to address for our research to be first class in terms of both excellence and impact?

Cluster 8: Other Storage approaches

- High capacity, low loss capacitors. Not just solid state, also electrochemical.
- Synthesis of fuels electrochemically, not just H_2, for storage
- Efficient use of O_2 from H_2 electrolysis
- Other electrochemical phenomena we could use as storage? Osmosis,
- Stable porous membranes for gas separation
- CO_2 as an energy vector or within storage systems.
- New materials for gas separation
- High temp CO_2 electrolysis, efficient electrodes
- Low temp CO_2 elec, using anode system. E.g. some alkaline membrane
- Microbial systems

- Linking CO2 electrolysis to carbon capture from power stations. i.e. get flexibility from power stations but powered by RE.

- How can you compare new tech with what's already out there?
- Electrocatalytic materials for CO2 electrolysis
- Electrodes for other element batteries. Magnesium ion battery? Long term idea

- New designs for redox flow batteries
- Solar fuels – new materials and devices
- Using solar to add to electrocatalysis.
- Electrocatalysts for CO2 electrolysis
- Improved ionic membranes for gas separation

- Thermoelectric materials? Is this electrochemical?
- Large scale batteries for solving grid intermittency.
- Reversable fuel cells as electrolysers
- Advanced manufacturing processes for membrane materials.
- Molten salts for storage

- *Immediate challenge?* – not so much.
- Sometimes you can tolerate low efficiency if something is scalable and cheap – e.g. methanol FCs.
- Need robust, critical review. Need to be happy to drop ideas. Not only start, also stop.
- Pulling plug on funding can be extremely damaging. See DOE experience of FC funding. Very problematic when you want to restart research again.

Cluster 9: Fundamental understanding of materials and interfaces for better performance, lower cost, more reliable technologies

- Underpinning theme therefore more difficult to characterise into timeframes.

- Better proton conductors for PEM FCs.
- New SO FC conductors which work at low temp
- Lost processes in PEM FC catalysts – immediate
- Less sensitive PEM membranes to h
- Stable alkaline membranes which can allow non PGM catalysts
- Alternative catalyst supports to carbon for PEM FC to avoid corrosion.
- Better O2 evolution catalysts for FC and electrolysers

- Computer simulations which are genuinely predictive
- Studying bond formation in real time. Techniques which can look at
- Getting rid of precious metal catalysts
- Electrode electrolyte interfaces.

- Need for more efficient anodes for SOFC which can use dirty fuel (e.g. with sulphur)
- Need for more efficient cathodes for SOFC
- Interfaces changing over time. Long term cation diffusion

- Can we solve the limitation of modelling? Modelling suggests cations not a problem but experimentally not true.
- FC electrolyser dual system in one unit.
- High temp FC material (200-500 degrees) – new Electrolytes
- Still focus on proton or move to hydroxide
- Key degredation issues

- O2 evolution at electrodes is important for FC and batteries. Major limit
- Materials processing – understanding of this. Step between matierla and device gets ignored
- Characterising the device not just materials
- Can we make usefully predictive quality factors for materials.

- New experimental tools for looking at materials under operating conditions
- New computational tools – surfaces and interfaces – harder than bulk properties
- Understanding degradation mechanisms
- New membranes – ionic conductors leading to new designs
- Understanding degredation to allow accelerated ageing tests
- Imaging and spectroscopy to look at degradation
- In-situ characterisation tool
- Non-nickel electrodes
- Si-Sn electrodes
- Lifetime testing – accelerated testing + long term in situ testing.
- Understanding dentric growth in batteries. Safer large scale non-cobalt batteries. (bigger batteries = more dangerous, therefore need to tackle this).
- Recovering Li-Ion components within batteries

Higher level ideas prompted at this stage….

- Techniques to separate ionic and electronic conduction. Ones usually a problem but hard to tell which
- Criteria to focus device work on materials which have a good chance to increase efficiency. E.g. seen that ethanol will never be an efficient system
- High energy batteries need safer electrolytes
- Efficient all solid-state Li-ion battery for safety. Separating individual solids will be challenging.
- Getting design characteristics from looking at the device level.
- Disconnect between modelling and experimental communities
- Modelling still struggles with interfaces. Very little work in this area.

….leading to the identification of underpinning challenges

- Many of these are enabling techniques and tools which underpin lots of things.
- Long term goals – lifetime testing – but this is also underpinning.
- A lot of suggestions are incremental.
  - But new materials can be transformative
  - 30 years ago, techs we talk of now were not even thought of.

- 10 years from lab to device for batteries is possible (and seen historically) and very impressive compared to other fields. Really shows the potential for new materials.
- Immediate challenges are not necessarily quick to achieve.

Q2: To address these challenges, what do we need in place?

- Targets are helpful
- We have grand challenges, but these are scientific, not devices. We need grand challenges to be linked to industrial engagement, in the long term. Not existing in this area.
- Need target like the US DOE. Very helpful to researchers. Setting targets for each area of work is important. Process of setting targets is useful.
- But targets must always be revisited. US DOE target in H2 storage not so helpful.
- In UK we use DOE targets anyway, but these are focussed on US applications so not best for UK. Could align with EU.

Economics and political will

- Difficult since international problem. Hard to get proper international research. Proper e.g UK-US long term grants (exception is EU).
- Currently hard for UK universities to join EU projects since you lose money because you only get a % of funding required.
- Conclusion: needs to be long term funding. If they are solved, benefits UK industry – new spin-outs and existing companies. Therefore, *need* to feed into existing UK industry. UK jobs and growth from taxpayer money. Research must benefit existing and *new* companies. Should show link between research outcomes and industry benefit.
- Cultural problem – universities won't touch a project which they are not going to make money from. Less culture of academic excellence.
- General issue of international collaboration. Not just EU but internationally
- EU projects can be very effective. However, collaboration just for the sake of it drains valuable ideas from UK institutions. Need to justify what the benefit coming back to the UK is.

Capabilities and capacities

- Central facilities – e.g. neutron sources, synchrotrons. Have it but need to maintain it. Trouble of synchrotron not being able to pay electricity bill and so cutting up-time is ridiculous.
- Need to strengthen industry links. UK tax money should feed into UK system. But can't just do research focussing on one or two companies.
- But what is UK these days? Companies are global. Research can still be valuable to the country even by working with international business. So industrial engagement is key, even internationally.
- Research base is key. And this needs to not be too diffuse. Need critical mass in particular areas.

Ways of working?

- We should be working with long-term approaches.
- Should we have a Fraunhofer type institute?
    - Could we create this within the existing institutes? Set in a university.
    - But needs to be seen as independent. This is challenging being within a university.
    - But need permeable boundaries so people are not excluded from such an institue
    - NPL is the closest we have, could this be extended and grown.
    - Could do it in a small number of universities to avoid exclusion.
    - Why has Fraunhofer worked so well? Is it just because Germany spends much more and have a big manufacturing base.

- We need to change industry. Build a strong industry base. Not sell off SMEs but grow them. Hard to engage long-term with industry which is headquartered in Japan.
- Industry will not spend money at universities if they can do it themselves. Either work on understanding fundamentals, or industry doesn't have the equipment or capabilities.
- Industry collaborations require freeing up of IP on both sides. Long term IP frameworks required. Think about more licensing agreements.
- Need to bring disciplines together better. Carving up £1m prevents you engaging with many disciplines. So need bigger funding pots so you can include more desciplines.
    - But not just different disciplines for the sake of it.

Whose job should it be?

- Universities/academic community. Maybe not currently the case, but they should be.

Coordination and alignment

- Do we need better coordination between uni departments?
    - This doesn't happen well because uni's don't fund projects; projects are funded externally and given to individual projects.
    - But uni's can guide coordination by building big pieces of equipment which people are then drawn too.
    - This could also be done through funding mechanism.
- Need critical mass and long-term investment.
- Need to be able to properly do high risk research. High-risk proposals are too often dismissed by peer-review panels. But long term targets require risk.
    - But need coordination to do this.
- Coordination is needed to ensure there is a balance between long-term speculative things, and short term immediate challenges. To ensure that not everyone is working on Li-ion batteries. Some overlap required but not too much. Balance portfolio.

Funding philosophy

- Need long term thinking
- Need a strategy in place and then you can put the people where they are needed and provide the needed training.
    - Need to coordinate training. CDT producing 40 phd's in FCs requires lots of jobs in FCs so that these PhDs go on to use their skills and don't lose these by going to work in e.g. management consultancy.
- Do very small companies need a Fraunhofer to do contract research? Short term research may not get you a PhD so may need to be done somewhere else.
- But electrochemical energy is less close to contract research. This research has harder, bigger challenges, which is less likely to be funded through contract research.
    - This makes funding coming from industry is more challenging and largely limited to 'cheap' PhDs, but not post-docs or bigger projects.
    - Need collaborative frameworks, since these big issue questions are still very interesting for industry.

Group 4: Hydrogen and other forms of storage

This group chose to address Question 1, "What are the main research challenges we need to address for our research to be first class in terms of both excellence and impact", for all three clusters under consideration, and then address question 2, "to address these research challenges what do we need in place", in a cross-cutting fashion

Question 1: What are the main research challenges we need to address for our research to be first class in terms of both excellence and impact?

Cluster 11: Implementing hydrogen as a sustainable energy vector

- How can you generate, store and transport hydrogen. Have options now, none are ideal.
  - Generate via electrolysis.
  - Transport via pipeline.
  - Store via tank.
  - What are better options?
- Cars – range problems.
  - Problem is that batteries don't last – if you have replacement batteries, they may not be relied on to last as long as they did before.
- There's a lot of component design needed – but in the end we're describing what we already know. We need to start defining what we need to know in terms of targets and performance, and work towards that.
- Can buy a decent fuel cell at the minute, but it relies on platinum – not enough available in the world to supply a global demand.
- Need new materials – research challenge.
  - There's a lot still unknown about carbon.
  - Be useful to get rid of fluoride at the ion-exchange membrane as well. Cathode in fuel cells uses twice as much Pt as the anode – need to replace this first.
  - Reduce manufacturing costs and increase performance of fuel-cells, long-term and broad, but important.
- Prioritise characteristics – all these materials in a car do present a safety issue.
  - Cost – these vehicles are currently stupidly expensive – need them to be cheaper. If you can make a cheap, light car 2/3 the size, would this be an attractive proposition?
  - Realigning targets for flexibility and durability as well as safety.

Cluster 12: Capacitive storage

- Defines a 'multi-dimensional variable space' Capacitors are temperature- and current- dependent. Aqueous- versus non-aqueous. They are strange devices.
- What are the key targets, bearing in mind they are quite complex?
  - Targets – what we're interested in is a systems target whereupon they will be useful as a system component.
  - Super ca-battery – combination of capacitors and batteries.
  - Combining fuel-cells and capacitors – fuel-cells give base-load, capacitors can give peak-load.
  - What technological advances do you need to make supercapacitors economically viable in the UK?
- New materials – key parameters needed are well known.
  - Comes down to energy and power density – charging and delivery.
  - The temperature range of supercapacitors need to be increased – they are currently very narrow.
  - Lifetime isn't an issue though – no chemistry.
- To define research challenges, can you set a target, say an electric car capable of driving 300 miles?
  - Need to set targets that are reasonable and achievable – the US DOE set targets too high and failed as a result.

Cluster 15: Thermal storage

- If you look at the seasonal flow of gas pipes in winter/summer, difference in flow. Thermal storage – needed in system to deal with seasonal variations and reduce peak electricity.
- New materials for thermal storage needed. Energy content in low-grade heat still very high – that's why heat pumps are so effective.
- Condense the thermal stores into larger, less frequent ones. Community storage?
- Is there any research needed into cryogenic storage, or is it all off-the-shelf stuff?
- Applications and technologies are important – what is suitable for a vehicle may not be for grid-scale storage, for instance.
- Crudely-designed targets in research projects aren't anywhere near as useful as system-level targets, which provide a baseline for components to slot into the system.

Q2: To address these challenges, what do we need in place?

- New technology is always expensive – need to look long-term.
- Economic impact is very important to the current government – this is a problem for doing basic science and for training scientists and researchers.
- Often, there is no way to see the impact when doing research. Need apolitical funding, without government interference – good science does not lean left or right.
- Flexible and sufficient research space. If you want to make a device, you want to focus people on making that, not publishing journal papers. Need to refocus academic incentives so that making devices are awarded as well as publishing papers. Do we need more engineer/scientists (scientists or engineers with a broad base of knowledge in the other area)?
- Truly open competition for funding, but targeted calls. If you're in an university outside a DTC, it's a nightmare to find a PhD student – outside and CASE funding is the only way.
- Issue of DTCs as *the* training mechanism, and no more PhDs on grants.
- The starting salaries are very low – 70% or so higher in the US/Australia. In terms of recruitment, it's very tricky. Need a sustainable and directed career path from undergraduate to lecturer/professor.

Annex C - Detailed Outcomes of Research Cluster Cross-Community 'Deep-Dive'

Group A: Sustainability Issues (Cluster 2)

- Cost reduction - need to make things commercially viable.
- Let's handle this all in one big bundle. Take account of environmental costs.
- Need to balance different elements - sustainability, cost etc.
- Need to look at lifetime energy costs.
- Life cycle perspective needed.
- Identify critical elements and materials needed. Can we eliminate critical materials e.g. indium?
- Lots of processing is about thin layers. Few water-based materials. Mostly organic (and nasty).
- Search for non-exotic abundant materials. Bismuth and barium examples of things that may be banned.
- Remove/recycle scarce or dangerous materials.
- Stop research on intrinsically toxic materials? Screen new materials.
- Science that acknowledges engineering problems.
- Thin film deposition methods for all devices. Printing/deposition processes. Work with industry for this. Move to batch processing with scale-up.
- Process engineering input would be good. [note this links to non-energy manufacturing].
- Balance between lower performance if cheaper to manufacture. Again the lifecycle approach.
- Tension between glamorous materials research and making it happen commercially.
- Can we do water-based not solvent based technology. Industry wants water-based to avoid clean-up costs.
- Should we set targets for materials? But 3 times the life and half the performance is better.
- Lithium is inherently more dangerous as energy density goes up. They'll burn at some point.
- Lead acid batteries need to be away from house with ventilation. Safety comes at a cost.
- A lot of this is around batteries.
- Get rid of platinum group metals.
- SOFC - nickel is carcinogenic.
- Could grant applications be screened in terms of the materials?
- But counter-argument - don't close down areas before problems arise. Cadmium selenide can be used to demonstrate processes even if nasty in their own right. You can use it but have to meet recycling etc criteria.
- Materials processing/operation/recycle/disposal
- Thin film organics that could be applied across technologies.
- Printing uses organic solvents. Safe- or aqueous solvents needed.
- How to print/deposition a key issue. How to develop scalable, commercialisable techniques.
- In lab use acetone and evaporate – can't do that industrially. Should you do it in the lab as if it was in industrial application.
- Fuel cell companies have failed because complexity of the scaled process has imposed costs.
- What should we do in terms of targets. Difficult to do for a cross-cutting research,
- Targets need to be short, medium and long-term.
- How do you analyse and determine what is allowable and what is not? Cadmium telluride divides views depending in whether people use it.
- Performance Targets need to be embedded in particular technologies. Depends on the application.
- Immediate targets
- Identify elements of concern and alternatives
- Medium targets

- Production and testing alternatives
- Long term
- Concerns should be eliminated.
- Thin film deposition methods: non vacuum techniques. Sometimes EPSRC rejects PV bids to advanced manufacturing! Allegedly. Joining up within EPSRC. Next to nothing on thin film manufacturing within PV portfolio. allegedly thin film spend is not really.
- Immediate -standards for individual technologies.medium - meaningful comparisons across technologies.
- Three things:
    - LCA for technologies/applications. (Embedded energy). Use common methodologies.
    - Safety is an important performance criterion.
    - Critical materials.

- Younger researchers - training in sustainability.
- Affordability of technology goes up with development. Think about sustainability from the start. Develop new materials to drive down the cost. Substitutability of materials.
- Resources - natural, human, political resources. ID critical materials for emerging technologies. Non-rare earth metals. Non precious metal catalysts. Replacing lithium with na/mg. catalysts materials from abundant easily accessible elements.
- Batteries - increased safety and performance for specific applications.
- New materials better performance. Platinum alternatives.
- Substitutability to materials.
- Life cycle carbon impact. Policy inefficiency / CO2. Total cost analysis

- Cost reduction through improved materials use in m aura turning, improved lifetimes,
- Understand degradation Of bulk materials and interfaces.
- Recyclability and its cost. Techniques themselves need to be "sustainable"
- Heat management for safety in large scale applications.
- New thermoelectric materials for waste heat.
- Lower operating temperatures, eg SOFC.
- CO2 reduction for storing energy. Renewable fuels.
- Solar fuels for H2 andCO2
- How easy is to move to mass production - cost savings available?
- Improved fuel utilisation for fuel cells. (Use all of the fuel you've put in).
- Three buried treasures
    - Abundant materials
    - Alternatives to precious metals/rare earths.
    - Degradation mechanisms/Life cycle

Group B: Fundamental understanding of materials and interfaces (Cluster 9)

- Discussion of how to tackle this question. Ion transport is a fundamental materials issue.
- Challenges
    - Molecular modelling, computational, quantum mechanical modelling
    - Translating molecular modelling science into experimental measurements
    - Are there hierarchical scales over which different models should built?
- Need for a virtual centre for materials research?
- Or a data repository? There are issues with having a repository. Huge variety in materials and applications. Sharing sensitive data.
- Capability and capacities we need in place (roughly in order of technology readiness levels)
    - Molecular modelling and simulations

    - Need fast, available and cheap computers
    - User-friendly computer models to allow nonexperts in computing to be able to do these types of studies. This could take the form of a close collaboration alternatively
    - Validation via accessible (shared?) lab facilities. Including STFC/NPL?
    - Synthesis of new materials for specific applications (energy) applications
    - Application demonstration
- How can we do better?
    - Joint/joined up sharing of research with industry
    - 'Babelfish' between different scientific and engineering disciplines
    - Appropriate funding/support for international collaboration (eg IEA)
    - Genuine mobility of researchers, including PhD students, to bring added value to collaboration and facility use
- Who should do the research and who should fund it?
    - Academia with industry (not either in isolation)
    - Mobility between academia and industry
    - Strategic and coordinated research career development from PhD to Professor
    - Number of faculty positions versus postdocs – can we increase the ratio of faculty to postdocs? If not, more advanced fellowships embedded in long term research programmes?
- Economic and political will
    - Incentives for industry – stable support to support development of storage and conversion technologies
    - Sensible long term cost predictions
    - We should LEAD in many international programmes

- This means there should be a chance for materials to make a difference.
    - Application is critical – materials may be suitable for one not another, good to share
    - Interfaces are much less understood than the bulk
    - Identifying properties of interfaces which we care about
    - Developing tools to look at interface properties
- This could feed in to the need for a centre of collaboration where specialised tools can be used by other groups – such as NPL
    - User-compiled database
    - Standardised/shared protocols for simple measurements such as surface energy, work function/electropotential measurements
    - How to characterise interfaces
    - Size-dependent properties of interfaces
    - Ageing of interfaces
    - Reproducibility of interface properties – eg checkable experiments in publications where the checker gets some incentive/reward
- Computational tools to rationalise use of materials and materials combinations?
- Examples:
    - Electrode interfaces in batteries – look at surface chemistry properties over time through charge and discharge life. To do this, develop eg spectroscopic techniques.

Group C: User Behaviour and Demand (Cluster 14)

- Is this purely about reducing demand? Or simply managing it?
- Probably a lack of expertise in this group. Obviously a lot of the research challenge lies in socioeconomics. Particularly in education and sociology.

- There's only so much that can be done with technology in managing behaviour.
- Possibility for mandated local storage in new builds?
- There's a problem in selling complexity to the general public.
- Key Challenges:
    - Development of decentralised power technology. It's important to actually develop appropriate localised storage solutions before you can consider deploying it.
    - Difficulty of encouraging take up of that technology
- There's a need for research into better energy saving technologies
- Need for technology research to develop viable domestic scale storage, there's no point even trying to deploy a storage based system until these are improved. Key issues are understanding the safety concerns and in delivering sufficient lifetime (5-10y lifespan) and ease of serviceability.
    - Advanced lithium ion and aqueous chemistries seem most viable. Lead acid is probably the only real option currently.
- Need for psychological research into what is actually effective and incentivising behaviour change.
    - Need to survey what has already been learnt in this space.
    - Need to understand how this can be effectively translated into policy mechanisms.
    - Also need to better understand the barriers
- Developing autonomous power sources (localised, maybe hand held) might better link consumers to their energy consumption.
- Need to change the design philosophy in more domestic technologies, similar to the shift seen in CPU's from max power, to max energy efficiency. Particularly in applications that benefit twice from reduced cooling requirements.
- Very different challenges in remote (non grid-connected) environments

What do we need for this to happen?

- Main need is for education about the complexity of the grid – though as noted before people don't really want to learn! This requires a long term political agenda to adjust public perception, like recycling.
- There's a need to train service level personnel to maintain and install localised storage systems.

Group D: Hybrid Systems (Cluster 5)

- Can you see this as a materials challenge? Making multifunctionality in a project could save costs, but risky challenge.
- Smart control algorithms.
- Getting components to communicate properly.
- Combine PV power and long-term thermal storage.
- Heat management and electrical efficiency models for hybrid systems.
- Effect of hybridisation on durability. I
- Identify systems/applications where hybrids add value.
- Start thinking about hybrids when you design a material.
- Increase efficiency of thermal/electrical conversion efficiency by an order of magnitude.
- Are multifunctional materials the answer if one of the functions is suboptimal or not competitive?
- How can you model decoupled hybrids (e.g offshore wind, onshore storage) in terms of optimal placement and distance?
- Drive for hybridisation is to reduce cost, increase efficiency.
- To solve storage problems that one technology on its own cannot.

- You need to start thinking about the combination of different systems as soon as possible – interacting with the other development team very soon into the project, as unforeseen difficulties and differences in characteristics may occur.

- What capabilities need to be in place?
- Demonstrator test-beds.
- A context – what are you trying to achieve by hybridisation?
- Coordination and alignment – do you need a cross-community forum?
- If you want to make a hybrid, you need to characterise the problem first. You need demonstration sites to characterise the system and the interactions.

Things to report back:
- Funding for cross-topic PhDs – both materials and systems level
- Modelling Hybrid system scenarios to focus research effort on promising systems.

- Question: Is hybridisation useful?
- Future energy systems will be even more complicated than most people think – as they're about combining technologies rather than just a linear set of technologies.
- Research question – application of complexity theory. Does hybridisation add stability and security, as well as just flexibility?
- You need knowledge of the application in order to successfully hybridise a system – need to work from industry very early to maximise success.
- Mobility of academics and industrialists between academia and industry – equilibria formed. Knowledge sharing. Partnerships, internships etc.
- Who should fund it? EPSRC, TSB,industry, national grid.
- Should both industry and academia get support, or just academia?
- Doesn't need a new mechanism, existing mechanisms should support it.
- Much more coordinated career paths and plans right up to professor, longer-term postdocs to give stability.
- Have a continuity of a project or theme where people go all the way from PhD to lectureship.
- Long-term projects, maybe 10-years with 5-year review points. DECC and BIS need to be more engaged with research challenges.

Group E1: Issues of Scale (Cluster 13)
- Appropriate technology selection
- Lots of storage in cluster but should probably have some things around other tech, e.g. solar.

Q1: Research challenges
- Materials supply chain – not just rare, also production of polymers, especially with large up-scaling
- Which batt for which application?
- Monitoring state of health (degradation)
- Post-mortem analysis of batteries and analysis under real operating conditions.
- Recycling
- Predicting demand for storage in next decade.
- Predicting demand for storage in 6 hours' time

- Hybrid power trains
- Optimising control system for rate vs energy in battery output.
- Low cost grid scale batteries
- Real world monitoring
- Reversibility of electrochemical restrictions – relates to lifetime/degradation – need fundamental understanding around this.
- Top-down look on how tech will effect national system
- Short time issues – near casting energy system modelling – e.g. balancing PV.
- Comparison of cost/benefit of decentralised vs centralised storage.

- Cost for scale-up?

- New materials and chemistry for flow batts
- Developing dynamic models of electrochemical devices
- Power electronics.
-
- Novel redox couples
- Novel stack designs for large scale storage.

Is there an issue of scale with small systems – here issue of scale is in manufacturing. Materials availability, quality control, advanced/bulk manufacturing of nano-materials.

Q2: What needs to be addressed

Capabilities and capacities

Supply chain for materials

- Need to look for opportunities where the UK could contribute best.
- Global world so need to accept not all supply chain can be in the UK.
- Environmental costs, insurance costs are large in UK.
- Is the value in assembling the battery, or can we have value by making a specialist polymer
- We could compete in advanced manufacturing.
- Need flexibility in manufacturing, not just one product.

Demonstration facilities

Manufacturing equipment is maybe safer bet that manufacturing itself.

Access to right experimental facilities is a key issue

- A free electron laser would allow brilliant research into fast scale phenomena.

Co-ordination

UK has a very small electrochemical community.

- Need to build large community with good equipment to make good
- One university in china (e.g. Wuhan) has more battery testing channels than is across the whole UK.

Linking science base to demonstration would be a good step

We have no UK roadmap and so have no plan on what we should be doing to make us distinctive.

- Need strategic planning across institutions.

Long term funding.
Need to expand the community

What makes Japan so good at doing batteries?

- Good national labs for testing
- Long term funding from companies
- They have the resource
- Companies know they will ultimately deliver so happy to invest 'baseload' funding.
- Japanese culture looks in 5-10 year timeframes, UK looks at 3month (till the next share meeting)

Could do big focused project- Manhattan 2 project in US.

Link to EU and US roadmaps – they've done this already.

Whose job?

BIS?
Funding from Horizon 2020

- But application is too big, need coordination and to be done collectively.
- Need to go to Brussels – lobbying for EU funding
- No office in Brussels to support UK research.

Poor engagement with UK companies. Better engagement would lead to easier funding

Economics/political will

No political will.
No roadmap.
Long term funding
Rate of return for universities is poor from EU funded projects so prevents engagement.

- Being funded for 50% of your costs means you lose money – it costs us money
- UK gives no supporting funding to solve this.

Universities' minister could help voice our needs?

Things that MUST be included in report

Strategic long term funding
Roadmapping
World class facilities – science, prototyping, large scale testing.

- We don't have institutes (like battery research institute)
- But some advantages to not having such institutes
- Fraunhofer has 50% industry funding. That wouldn't work here.
- Need for demonstrator sites.

Group E2: Issues of Scale (Cluster 13)

Can we use remote communities to demonstrate different technologies?

Even smart meters are perhaps not visible enough. Visibility and awareness is key to changing behaviour.

- This is simplified with solar technologies if you can make the mental connection between sunshine and cheap energy

Biggest barrier to domestic storage is feed in tariff.

Need to understand who the early-adopters are likely to be in this area

- If this can be correctly marketed this could increase deployment

Visibility could be increased by adding a carbon tax to electricity. Though this would need to be carefully managed to avoid exacerbating inequality between energy rich and energy poor.

- What mechanisms can be used that are effective at incentivising the energy poor (who have limited ability to invest in new technologies)?

Congestion charge given as an example of a very effective and popular(?) incentive scheme. Could this be a model for domestic electricity usage.

Vehicle to grid could be a key contributor in this area.

Three things that must be included

- Public education and awareness – need people to understand what storage is and what it can do with respect to CO2
- Research into effective incentives and barriers – need more innovative ideas in this space.
- Understanding attitudes to asset ownership – For example the rise in popularity of car clubs. In this model nobody has to care about the battery.

Annex D: Agenda

Tuesday 25th June	
10.15	Arrival and Registration
10.30	**Session One:** ***Introduction*** Introduction to the purpose and process of this Expert Workshop and the overall development plan to create an Energy Research and Training Prospectus
	Discussions and activities to share current thinking about the current research and research strategy for this sector.
12.15	Lunch
13.15	**Session Two:** ***Exploring the Research Themes*** Discussions and activities to identify and develop potential research themes from different perspectives
	Session Three: ***Reflection and Summary*** Activities to reflect on the various different emerging research themes and their relationships
17.30	Close
19.00	Drinks Reception and Dinner
Wednesday 26th June	
9.00	**Session One:** ***Introduction to Day Two***
	Session Two: ***Deeper Analysis of the Emergent Research Themes*** Discussions and activities to explore emergent research themes more deeply, with the aim of identifying drivers and barriers to these different future research themes
12.00	Lunch
13.00	**Session Three:** ***Further Development of Research Themes*** Discussion and activities to further shape the prospectus
	Session Four: ***Summary and Next Steps*** Short session to collate feedback on next steps for the research councils and to summarise the key outputs of the workshop, as well as the next steps in the development of the prospectus
16.00	Event Finishes

Appendix E: Attendance List

Surname	Forename(s)	Organisation
Aguadero	Aindara	Imperial College London
Black	Deidre	Royal Society of Chemistry
Book	David	Birmingham University
Brandon	Nigel	Imperial College London
Brownsdon	Lucy	Centre for Facilitation Services
Chapman	Nigel	Centre for Facilitation Services
Chen	George	Nottingham University
Claridge	John	Liverpool University
Cogdell	Richard	Glasgow University
Connor	Paul	St. Andrews University
Cruden	Andrew	Southampton University
Cusson	Edmund	Strathclyde University
Eames	Philip	Loughborough University
Emmott	Christopher	Notetaker
Forbes	Ian	Northumbria University
Foster	Sam	Imperial College London
Fu	Chaopeng	Oxford University
Gottschlag	Ralph	Loughborough
Gregory	Duncan	Glasgow University
Hall	Peter	Sheffield University
Hardwick	Laurence	Liverpool University
Irvine	Stuart	Bangor University
Kammerer	Iris	Fellowship Team
Lilley	Scott	St Andrews University
Mays	Tim	Bath University
Nelson	Jenny	Imperial College London
Newborough	Marcus	ITM Power
Preece	Lewis	EPSRC
Radcliffe	Jonathan	Birmingham University
Rhodes	Aidan	Fellowship Team
Robertson	Neil	Edinburgh University
Sharman	Jonathan	Johnson Matthey
Skea	Jim	Fellowship Team
Slade	Robert	Surrey University
Slater	Peter	Birmingham University
Thijssen	Job	Edinburgh University