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Research Councils UK Energy Programme Strategy Fellowship

ENERGY RESEARCH AND TRAINING PROSPECTUS: REPORT NO 6

ELECTROCHEMICAL ENERGY TECHNOLOGIES AND ENERGY STORAGE

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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 RCUK 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 RCUK 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 was to synthesise an Energy Research and Training 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 contributes to the evidence base upon which the RCUK Energy Programme can plan activities alongside Government, RD&D funding bodies, the private sector and other stakeholders. The Prospectus highlights links along the innovation chain from basic science through to commercialisation. It is intended to be a flexible and adaptable tool that takes 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 has been a series of four high-level strategic workshops and six in-depth expert workshops which took place between October 2012 and July 2013. The main report, *Investing in a brighter energy future: energy research and training prospectus*, was published in November 2013. This is one of nine topic-specific documents supporting the main report. All reports can be downloaded from: www3.imperial.ac.uk/rcukenergystrategy/prospectus/documents/reports. This first version of the Prospectus will be reviewed and updated on an annual cycle during the lifetime of the Fellowship, which ends in 2017.

This report is the product of work conducted independently under EPSRC Grant EP/K00154X/1, Research Councils UK Energy Programme: Energy Strategy Fellowship. The draft report was reviewed by XXX. While the report draws on extensive consultations, the views expressed are those of the Fellowship team alone.

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Executive Summary

This report examines electrochemical energy technologies, which includes solar photovoltaic (PV), fuel cells hydrogen technologies and batteries, as well as other energy storage technologies. These technologies were gathered together for this Prospectus report due to commonalities in the basic science and research skillsets required for research and development (R&D). The conclusions from a two-day, facilitated expert workshop attended by academics along with representatives from the private sector and public sector organisations has been one of the most important inputs to this report. The report sets these conclusions in the context of the UK's scientific and industrial capabilities, policy ambitions, global and UK developments and outputs from existing roadmaps and needs assessments.

The main findings are:

- Basic research in physics, chemistry and materials science directly feeds in and helps develop electrochemical technologies, and such 'blue-sky' research is important in ensuring the UK attains and keeps a competitive edge in these areas.
- A strategic framework for the electrochemical sector would be useful to establish major challenges, identify areas of cross-collaboration between research groups and provide a simple overview of research efforts, allowing easier identification of collaborative efforts.
- Test facilities and infrastructure are essential in ensuring innovations can progress from basic laboratory prototypes to demonstration products. This was seen as underfunded in the UK, and investment at this stage should be seen as important. Ensuring that researchers can gain timely access to Science and Technology Facilities Council's (STFC's) analytical facilities and infrastructure is also key in this sector.
- In many cases, the technologies and research described in this report will not reach technological maturity for years or decades. Long-term support for this research is thereby important in ensuring that the UK will gain the eventual benefits from this work. Moves towards long-term planning and strategic roadmapping will help the UK remain internationally competitive in these fields.
- To maximise success in developing and commercialising technologies of this nature, linkages between academic researchers and industry should be made very early in the research process. Joint and joined-up research with industry, particularly in areas such as materials modelling, could accelerate the development process.
- There should be opportunities for researchers to follow career paths that are sustainable, offer significant development and can lead them through their career from undergraduate to professor. This would allow promising new researchers to enjoy greater career certainty and could attract good candidates from industry.
- Databases of results and properties of materials should be made available to the community, either centrally curated or user curated with a centralised index. Support should be provided to resolve intellectual property (IP) issues where applicable.
- PhD training should be designed so that the skills attained can remain relevant even if the industry radically changes. A balance between the acquisition of deep skills and wider transferrable skills is needed. Centres for Doctoral Training (CDTs) should be supplanted by project- and discipline-based studentships where appropriate. Industrial Collaborative Awards in Science and Engineering (CASE) awards should be pursued and extended where possible.

Acronyms

2DS	two degree scenarios
BBSRC	Biotechnology and Biological Sciences Research Council
BIPV	building integrated photovoltaic
BIS	Department for Business, Innovation and Skills
CASE	Collaborative Awards in Science and Engineering
CCS	carbon capture and storage
CDT	Centre for Doctoral Training
CHP	combined heat and power
CPV	concentrated photovoltaic
DECC	Department of Energy and Climate Change
DOE	Department of Environment (US)
DSM	demand-side management
EC DG	European Commission Directorate General
EERA	European Energy Research Alliance
EII	European Industrial Initiative
EPSRC	Engineering and Physical Sciences Research Council
ESME	Energy Systems Modelling Environment
ESRC	Economic and Social Research Council
ETI	Energy Technologies Institute
ETP	Energy Technologies Partnership
FCEV	fuel cell electric vehicles
FCH-JU	fuel cell and hydrogen - joint understanding
FP7	Framework Programme 7
GHG	greenhouse gas
GW	gigawatt
H^+	hydrogen
HFCEV	hydrogen fuel cell electric vehicles
HGV	heavy goods vehicle
IEA	International Energy Agency
IP	intellectual property
KW	kilowatt
KWh	kiloatt hour
LC	low carbon
LCICG	Low Carbon Innovation Carbon Group
LCNF	Low Carbon Network Fund
MARKAL	MARKet Allocation (an energy systems model)
MCS	microgeneration certification scheme

METI	Ministry of Economy, Trade and Industry
MW	megawatt
NCIL	no clear international lead
NEDO	New Energy and Industrial Technology Development Organisation
NERC	Natural Environment Research Council
NVQ	National Vocational Qualification
PEM	proton exchange membrane
PV	photovoltaic
R&D	research and development
RCUK	Research Councils UK
RD&D	research, development and demonstration
REF	Research Excellence Framework
SET	Strategic Energy Technology (EU R&D plan)
SME	small and medium enterprises
STFC	Science and Technology Facilities Council
T&D	transmission and distribution
TINA	technology innovation needs assessment
TSB	Technology Strategy Board
TWh	terawatt hour
UKERC	UK Energy Research Centre
UKHFCA	UK Hydrogen and Fuel Cell Association

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1. Introduction

This document is one of a series of reports that sets out conclusions about UK research and training needs in the energy area. The focuses of this report are electrochemical energy technologies and energy storage. The primary audience is Research Councils UK (RCUK) which supports energy research in UK higher education institutions through the RCUK Energy Programme. However, other bodies involved in funding energy research and innovation, notably those involved in the UK's Low Carbon Innovation Carbon Group (LCICG) may also find the content useful. The report is also being disseminated widely throughout the UK energy research and innovation community to encourage debate and raise awareness of the work conducted under the Fellowship.

The Fellowship team is using the EU/International Energy Agency (IEA) energy research and development (R&D) nomenclature[1] to map out the energy research landscape. This report covers Group II **Renewable Energy Sources,** specifically section III.1.2 **Photovoltaics (PVs).** It also covers Group V **Hydrogen and Fuel Cells** and Group VI **Other Power and Storage Technologies** specifically VI.3 **Energy Storage.**

The report responds to a recommendation of the 2010 International Panel for the RCUK Review of Energy[2] that the research supported by the Research Councils should be more aligned with the UK's long-term energy policy goals. The key criteria used in developing this report have been the three pillars of energy policy – environment, affordability and security – coupled with potential contributions to UK growth and competitiveness.

The most important input to this report has been a two-day, facilitated expert workshop held in June 2013. There were 36 attendees at the workshop (excluding the Fellowship and facilitation team), most of whom were academics and researchers falling within the community supported by the Engineering and Physical Sciences Research Council (EPSRC). In addition, a number of attendees were from private sector and government organisations. A full report of the workshop has previously been published as a working paper[3]. The working paper was the document of record and has acted as an intermediate step in the production of this report which focuses on key messages and recommendations. The workshop also drew on the outcomes of a series of 'strategy' workshops which addressed: **energy strategies and energy research needs; the role of the environmental and social sciences**; and **the Research Councils and the energy innovation landscape**. Reports of these workshops are also available on the Fellowship website[4].

This report is structured as follows. Sections 2-4 provide the wider context within which research and training challenges are identified. Section 2 focuses on the possible role of electrochemical energy technologies and storage in future energy systems both globally and in the UK. Section 3 describes the current UK research landscape and capability levels. Section 4 reviews existing roadmaps and assessments of research and innovation needs. Sections 5-9 draw heavily on the Oxford workshop. Section 5 sets out high-level research challenges in the three areas upon which the workshop focused. Section 6 delves more deeply into these research challenges and identifies specific research questions that need to be addressed. Section 7 focuses on the ways in which the Research Councils operate, how the research they support is conducted and underlying needs for research infrastructure and data

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1 European Commission 'Energy R&D statistics in the European Research Area', 2005, http://ec.europa.eu/research/energy/pdf/statistics_en.pdf

2 RCUK, 'Progressing UK Energy Research for a Coherent Structure with Impact', 2010, http://www.epsrc.ac.uk/SiteCollectionDocuments/Publications/reports/ReviewOfEnergy2010PanelReportFinal.pdf

3 RCUK Energy Strategy Fellowship, 'Electrochemical Energy Workshop Working Paper', 2013, http://www3.imperial.ac.uk/rcukenergystrategy/prospectus/workshops/workshop9

4 RCUK Energy Strategy Fellowship website, http://www3.imperial.ac.uk/rcukenergystrategy/

collection/curation. Many of the conclusions are generic in the sense that they may be applicable beyond the electrochemical energy and storage areas across the energy domain or even more widely. Section 8 addresses training provision. Section 9 addresses generic issues about the role of the Research Councils within the wider UK energy innovation system and EU/international engagement.

2. Current and Future Roles of Electrochemical Energy Technologies and Energy Storage

2.1 Global perspectives

This report examines electrochemical energy technologies, which includes solar PV, fuel cells, hydrogen technologies and batteries, as well as energy storage technologies.

2.1.1 Solar PVs

PV cells convert sunlight to energy via photoelectric processes. Only existing in niche markets and technology demonstrators prior to the turn of the century, the growth in production of PV modules globally has followed an almost exponential curve, as can be seen in Figure 1. The total cumulative production of PV cells stands at approximately 102 GW as of 2012.

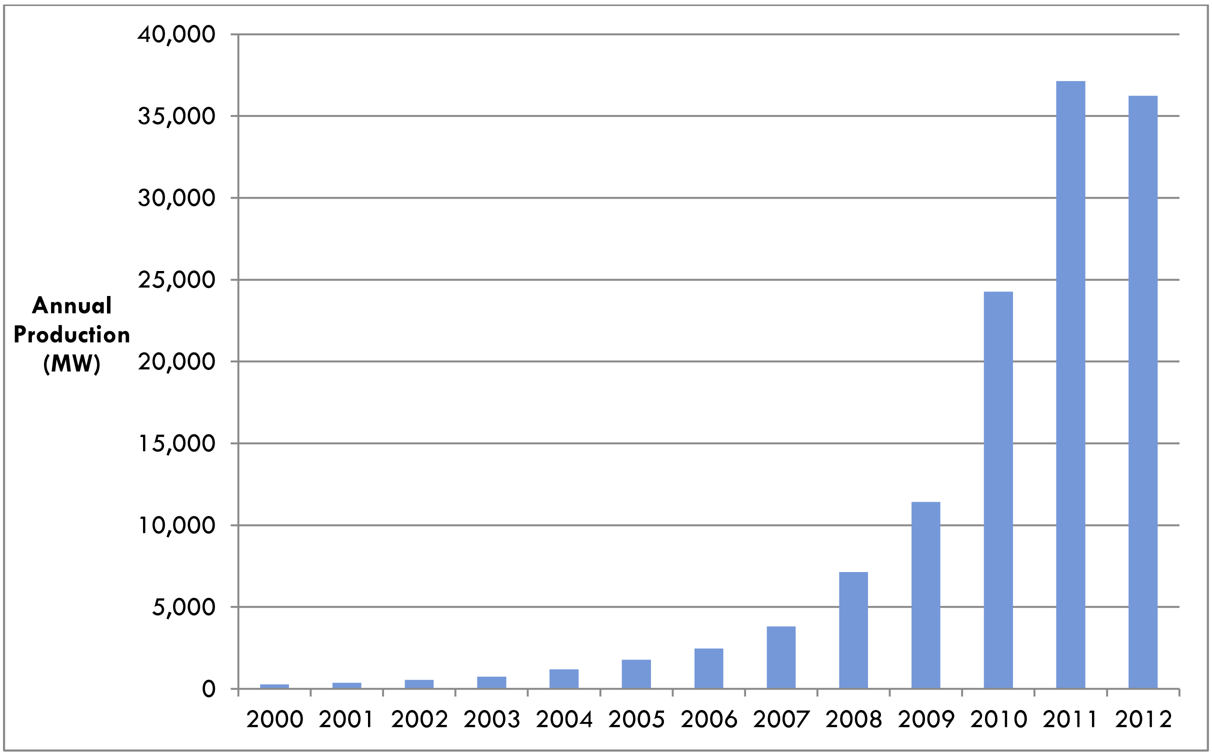

Figure 1: Annual Global Production of Solar PV Cells 2000-2012 (source Earth Policy Institute)

The most common solar cells in use today utilise crystalline silicon as the light-absorbing semiconductor~~interface ma~~, though thin-film PV technologies (materials deposited on a glass substrate) provide a growing segment of the market. The last few years have seen a substantial ~~precipitous~~ drop in the price of PV cells, driven by considerable increases in supply of low-cost crystalline silicon, generous subsidies for installation in some EU countries and a rapid expansion of low-cost manufacturing facilities in China. It is estimated that worldwide prices of PV modules dropped 80%

between 2008 and 2012[5]. Future drops in cost and improvements in efficiency are expected, with the US Department of Energy predicting a 75% drop in costs between 2010-20, with an average cost per watt of between $1-1.50, depending on size and siting.

A comparison of two scenarios modelling future global electricity capacity, the IEA's Energy Technology Perspectives (ETP) two degrees scenario (2DS)[6] and the Mountains scenario from Shells New Lens Scenarios[7], reveals some interesting perspectives. The Shell Mountains scenario forecasts a greater percentage of electricity supplied from solar PV by 2050 than the IEA scenario – 13% compared to 6%. This is despite the Shell scenario as a whole being greatly more CO_2-intensive than the 2DS scenario, with over twice the carbon emissions forecast by 2050. The counterpart Shell Oceans scenario is even more ambitious for solar PV, with a prediction that solar PV will become the dominant electricity source by 2100.

Shell attribute this dominance to the rapidly-dropping price~~cost~~ of solar, with reports from UBS[8] and Deutsche Bank suggesting that solar will be able to compete on an unsubsidised basis in many national electricity markets in the next couple of years, as well as developing countries in Asia and Africa favouring distributed PV over centralised grids in the future. While the global future of solar is still uncertain and many other scenarios from major energy suppliers do not share this optimistic picture, current trends in solar PV point towards a positive future for the technology.

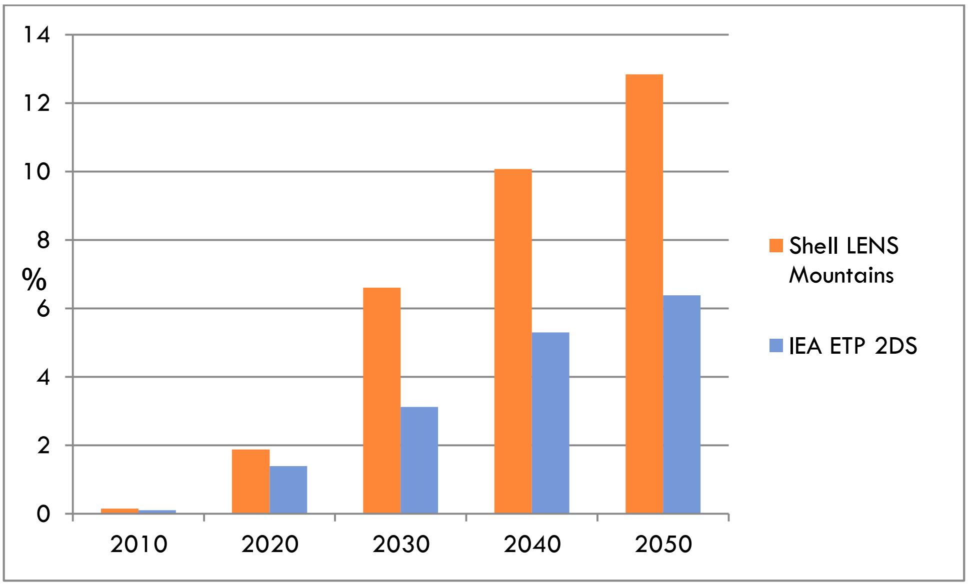

Figure 2: Solar PV percentage of electricity generation in Shell LENS and IEA ETP scenarios

2.1.2 Fuel Cells and Hydrogen

A fuel cell converts the chemical energy from a fuel into electrical energy via a reaction with an oxidising agent. There are many variants of fuel cell, using different configurations and fuels, including hydrogen, ethanol, methanol natural gas, diesel and others. The basic design characteristics of all are the same, however, with an anode, cathode and ionically conducting electrolyte. The principle of the

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5 Bloomberg New Energy Finance, **'Reconsidering the Economics of Photovoltaic Power'** http://www.bnef.com/WhitePapers/download/82

6 IEA, **'Energy Technology Perspectives 2012'**, http://www.iea.org/etp/

7 Shell, **'New Lens Scenarios'**, 2013, http://www.shell.com/global/future-energy/scenarios/new-lens-scenarios.html

8 UBS, **'The Unsubsidised Solar Revolution'**, 2013

fuel cell has been around for over 150 years. However large stationary units for satisfying large-scale electricity demand are a relatively recent development.

Fuel cells can serve many roles in the energy system, depending on size, siting and characteristics. Larger, stationary cells can be used as off-grid power sources, backup power for industrial plants and other facilities such as hospitals, and as co-generating combined heat and power (CHP) systems. Domestic-sized fuel cell CHP systems can be used as boiler replacements, providing both electricity and heating to a property.

Fuel cells can also be used in transportation, in fuel cell electric vehicles. There are no commercially-available models of hydrogen fuel cell car available currently, though several major manufacturers are claiming they will begin commercialisation in 2015. Over 100 fuel cell buses have been deployed for testing in cities across the world. **Prospectus Report 4: Transport Energy** covers this topic in more depth. The hydrogen economy, a concept in which generated hydrogen is used as an energy carrier to displace hydrocarbons in vehicles and other end-uses, has been proposed for several decades, although major research and deployment challenges still remain in hydrogen transportation, storage and efficient, low-carbon generation. Global hydrogen production for use as an industrial feedstock is considerable at present – approximately 60 million metric tonnes are produced annually, mostly from hydrocarbons, with an energy content equivalent to 10% of world electricity production[9].

The IEA 2DS scenario has three variants for the quantity of hydrogen used – standard, high-hydrogen and no-hydrogen. The no-hydrogen scenario assumes no commercial penetration of hydrogen fuel cells in any sector. In the standard 2DS scenario, fuel-cell vehicles reach significant market share by 2040, and make up 13% of total passenger vehicles and 7% of truck stock by 2050. Hydrogen begins to be used in the industrial sector as an energy source, but makes no headway into the buildings sector. In the high-hydrogen scenario, fuel-cell vehicles reach a significant market share by 2030, and by 2050 reach proportions twice that as in the standard scenario – 27% in passenger vehicles and 14% in trucks. Hydrogen is used for steel production and in the petrochemicals industry, and co-generating fuel-cell units will provide 5% of residential energy needs.

The Shell Mountains scenario is quite favourable towards fuel cells and the hydrogen economy, forecasting an uptake in the 2020s of hydrogen transport infrastructure, firstly in localised urban areas, and then spreading to regional grids. By 2060, the scenario forecasts global transport uses of hydrogen to overtake industrial demand, mainly driven by passenger vehicles.

2.1.3 Energy Storage

Energy storage technologies store energy, usually electricity, for release at a later time. Energy storage technologies such as pumped hydro plants have been built for the past eighty years, but the emergence of intermittent and non-flexible generation such as wind, solar and nuclear has renewed interest in large-sale, network-level energy storage. There are several different storage technologies – batteries, flow cells, compressed air storage, flywheels, supercapacitors, thermal, storage as hydrogen and pumped hydro are some examples. Of these, pumped hydro accounts for more than 99% of bulk capacity worldwide. Network and system level integration of energy storage technologies are covered in **Prospectus Report 10: Energy Infrastructure**. This report looks at R&D of component storage technologies.

Estimations of the quantity of energy storage to be deployed worldwide are difficult due to considerable uncertainties. The IEA ETP 2DS scenario forecasts that by 2050 approximately 1% of global power production will be routed through energy storage. This is at a variable renewable

[9] **Chemical Economics Handbook**, 2008, http://www.ihs.com/products/chemical/planning/ceh/index.aspx

energy penetration of around 20%, and the report states that the economic value of storage will increase as the penetration of variable sources goes up. Specific storage technology forecasts are more difficult to produce, due to uncertainties about development and cost reduction, as well as the need to compete economically against backup generation and demand-side management technologies. The deployment of grid-level storage on a large scale also depends on the market and regulatory makeup of a country's electricity system.

2.2 UK Energy Futures

2.2.1 Solar PV

The rate of solar PV installations in the UK has greatly increased since a feed-in tariff for domestic and small commercial installations was introduced in April 2010. The tariff rate was originally set at 43.3p/kWh for domestic installations, but has dropped gradually to its current rate of 14.9p/kWh in response to a steep decline in the cost of solar panels, dropping up to 50% between summer 2011 and March 2012~~, and concerns regarding the funding of the scheme~~. In 2009, the UK had 22MWp of grid-connected solar PV installed. By the end of 2013~~2~~, installed PV capacity~~ demand~~ in the UK had reached~~-~~ 2~~1~~.8~~6~~GWp.

The 2012 update of the Department of Energy and Climate Change (DECC) Renewable Energy Roadmap[10] featured solar PV for the first time. DECC estimates that between 7-20GW of solar PV could be installed in the UK by 2020, providing between 6-18 TWh annually. This growth would be driven mainly by smaller scale, less than 50kW installations, mainly found on domestic and small commercial properties.

Three main tools are available for assessing long-term prospects for UK energy, greenhouse gas (GHG) emissions and technology deployment: the DECC 2050 Pathways Calculator; the UK Energy Research Centre (UKERC) MARKet ALlocation (MARKAL) model; and the Energy Technologies Institute (ETI)Energy System Modelling Environment ESME model.

These tools have largely been used to assess UK energy futures in the context of achieving the legally binding target of reducing GHG emissions by 80% below 1990 levels by 2050. This target is roughly compatible with the global IEA 2DS scenario discussed above and will, almost automatically involve the deployment of low carbon (LC) technologies and the displacement of fossil fuels.

Neither the UKERC Reference (REF) or central LC scenario involves any significant deployment of solar power in the UK. The DECC REF pathway also involves no deployment of PV. However the central Alpha scenario has an installed capacity of 70.4GWp by 2050, providing 59.9TWh a year. The lack of installed PV in these scenarios, apart from DECC Alpha, compared to the global scenarios could stem from the fact that they were completed in 2010-11, before the dramatic drops in installed PV costs witnessed in the last couple of years. The difference could also reflect the UK's relative unsuitability for PV systems, given its high latitude and electricity demand peaks occurring during the evening~~at night~~.

2.2.2 Fuel Cells and Hydrogen

Fuel cells and hydrogen, as in other nations, are still at a development and demonstration phase in the UK, with relatively few commercial applications at present. According to the UK Hydrogen and Fuel

[10] DECC '**Renewable Energy Roadmap: Update 2012**' https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/80246/11-02-13_UK_Renewable_Energy_Roadmap_Update_FINAL_DRAFT.pdf

Cell Association (UKHFCA), there are over 100 UK companies and 35 academic research groups working in this area. There are substantial Technology Strategy Board (TSB) and DECC funded development and demonstration projects, adding up to over £6m in 2013.

The UKERC central LC scenario predicts a steady shift to hydrogen fuel-cell vehicles, beginning with heavy goods vehicles (HGVs) and buses in 2030-35 and beginning to penetrate the passenger vehicle market by 2050. This contrast with the global scenarios presented above, which foresee passenger vehicles driving the shift to hydrogen fuel-cells. Data for the number of stationary fuel cells in the UK by 2050 is hard to come by due to the considerable uncertainties in this still-developing market.

2.2.3 Energy Storage

Pumped-hydro is the only form of grid-scale energy storage deployed at scale in the UK, with the Dinorwig plant in Wales being the largest installation at 1,724GW. Other technologies, principally batteries and flow cells have received small-scale trials in the UK with the current largest being the Smarter Network Storage project funded by the Low Carbon Network Fund (LCNF).

Future scenarios for energy storage tend to be technology-agnostic, and in wider scenarios are often bundled with demand-reduction efforts to present a figure for peak energy demand. Imperial College produced a report for the Carbon Trust[11] in 2012, investigating the potential value of energy storage in a future UK low-carbon system. This suggested that the value of storage in the UK electricity system is dependent on the quantity of intermittent generation installed, with an estimated value of 10GW of distributed storage capacity in a 10GW system in a 2050 high renewables scenario as being approximately £10 billion, spread across the whole energy system. Storage requires careful siting and sizing to optimise value, however, with larger bulk storage facilities nearer generation and distribute smaller stores nearer consumers on the distribution networks.

2.3 Conclusions

Many of the technologies in this report are as yet not being deployed commercially at scale, and thus predictions of take-up and economic costing remain highly uncertain. Solar PV is the most developed electrochemical technology in this report, and take-up globally has exponentially increased over the past few years as a result of dramatic cost reductions and extensive government support. Assuming economic and installation trends continue, PV will become a major part of global electricity supply by 2050.

Fuel cells, hydrogen applications and energy storage technologies (excluding pumped hydro) are at earlier stages of development and demonstration, and therefore the outlook for these technologies is more uncertain and dependent in many cases on the installation of new infrastructure or intermittent generation.

[11] Energy Futures Lab, Imperial College London, '**Strategic Assessment of the Role and Value of Energy Storage in the UK Low Carbon Future**', 2012. http://www.carbontrust.com/media/129310/energy-storage-systems-role-value-strategic-assessment.pdf

3. Current UK Research Capabilities

3.1 Overview

This section is based on two sources of evidence: a) subjective judgements made at the first strategic workshop about UK research and industrial capabilities[12] in relation to energy infrastructure as well other energy areas; and b) peer-reviewed assessments of UK R&D capabilities documented through the UKERC Energy Research Atlas 'landscape' documents[13]. The UKERC Energy Research Atlas has one landscape document on electricity transmission and distribution falling fully within the scope of this prospectus. Landscape documents on hydrogen and carbon capture and storage have portions relevant to the scope of this prospectus.

3.2 Strategy Workshop

At the strategy workshop **Energy strategies and energy research needs**, participants were invited to consider various key features of a future UK energy system. In the first session, they were asked to specify what technology mix they **wanted** to see in 2050 (aspiration) and what they 'expected' to happen, given their knowledge of barriers, policy directions, technology limitations and other factors. In general, people's aspirations were aligned with a world in which a great deal of progress was made towards reaching climate goals. However, they 'expected' much slower progress to be made in deploying LC technologies in practice.

Figure 3, below, was the output of the second session of the strategic workshop. This figure plots subjective judgments as to how the UK's industrial capabilities in specific areas of energy research are mapped against 'relevance to UK energy futures' (environment, affordability, security, economic opportunity). Research areas to the left of the vertical axis represent areas where there is thought to be no clear international lead, or a clear lead has yet to be established. The size of the coloured circles represents a subjective judgment about the level of scientific capability in the UK.

An outline of the findings for the set of technologies covered by this prospectus report is below. Further detail can be found in the report of the workshop, **Energy Strategy Fellowship Report 2: Energy Strategies and Energy Research Needs.**

3.2.1 Solar PV

For solar PV, there was significant divergence between the 'expected' and 'preferred' values. On average, attendees 'expected' 10% of the UK's electricity generation to be made up of solar PV by 2050, but 'preferred' a value of 21%. This uncertainty is caused by a mixture of technological and policy challenges – whether PV panels can reach a price point at which they work unsubsidised in the UK, and if not, what level of subsidy government will continue to provide.

In the second session, solar PV was rated average for criticality to the UK's energy futures, meaning that it was thought to be a useful but not essential technology. While there was thought to have a high UK academic capability in solar PV, industrial capability was ranked significantly lower, with the UK's capability thought to be one of the lowest of the energy technologies surveyed.

[12] RCUK Energy Strategy Fellowship, 'Report 2: Energy Strategies and Energy Research Needs', http://www3.imperial.ac.uk/rcukenergystrategy/prospectus/workshops/workshop0

[13] UKERC Energy Research Atlas, http://ukerc.rl.ac.uk/index.html

3.2.2 Fuel Cells

Stationary fuel cells were considered under heat supply technologies. Once again, there was a divergence in 'expected' and 'preferred' values, 9% compared to 18%. Fuel cells were expected to be relatively minor players in the 2050 market, even under the best-case 'preferred' scenario, with heat pumps, solar thermal and conventional boilers all playing bigger parts.

Fuel cells were rated as a non-critical technology for UK energy futures, ranking in the lowest third of the chart. UK academic capability in fuel cells was rated very highly, though industrial capability was ranked average. Some participants considered the fuel cell sector to be too early in commercial development to easily judge, and currently having no clear international lead.

3.2.3 Hydrogen

Hydrogen vehicles were considered under transportation technologies. Hydrogen vehicles were predicted to be a significant part of the 2050 transportation fleet, with 'expected' values having a mean of 19% and 'preferred' values averaging 32%. These shares are roughly in line with battery-electric vehicles, internal-combustion engine vehicles and plug-in hybrids in the 'expected' values, with the 'preferred' values roughly in line with plug-in hybrid vehicles, but significantly below battery-electric vehicles.

Participants thought hydrogen would play a stronger role in the UK than other fuel-cell technologies in the long-term, and could potentially play a large role in the transport sector, though still ranked it as below average for relevance to UK futures. The UK was considered to have a far lower industrial capability for hydrogen than for fuel cells, due to the additional transport, generation and storage challenges, though academic capability was regarded as strong. Once again, some participants regarded this as a sector in which the majority of activities are currently pre-commercial, and no clear international leadership has been defined.

3.2.4 Energy Storage

Energy storage was not directly considered in the first exercise, however a section on 'disruptive technologies and scenarios' brought out the potential for flexible demand and load-shifting to enable disruptive business models and services.

In the second session, participants ranked energy storage as highly relevant to the UK's energy future, placing it in the top half of the chart. UK academic expertise was rated lower than for the other technologies in this prospectus, with participants ranking academic expertise as 'medium' rather than 'high'. Industrial expertise was ranked as better-than-average overall, though many delegates again thought that there was no clear international lead in this sector. There was a view, however that this sector could undergo major growth in the future, as intermittent and distributed forms of energy begin to form large portions of the electricity supply.

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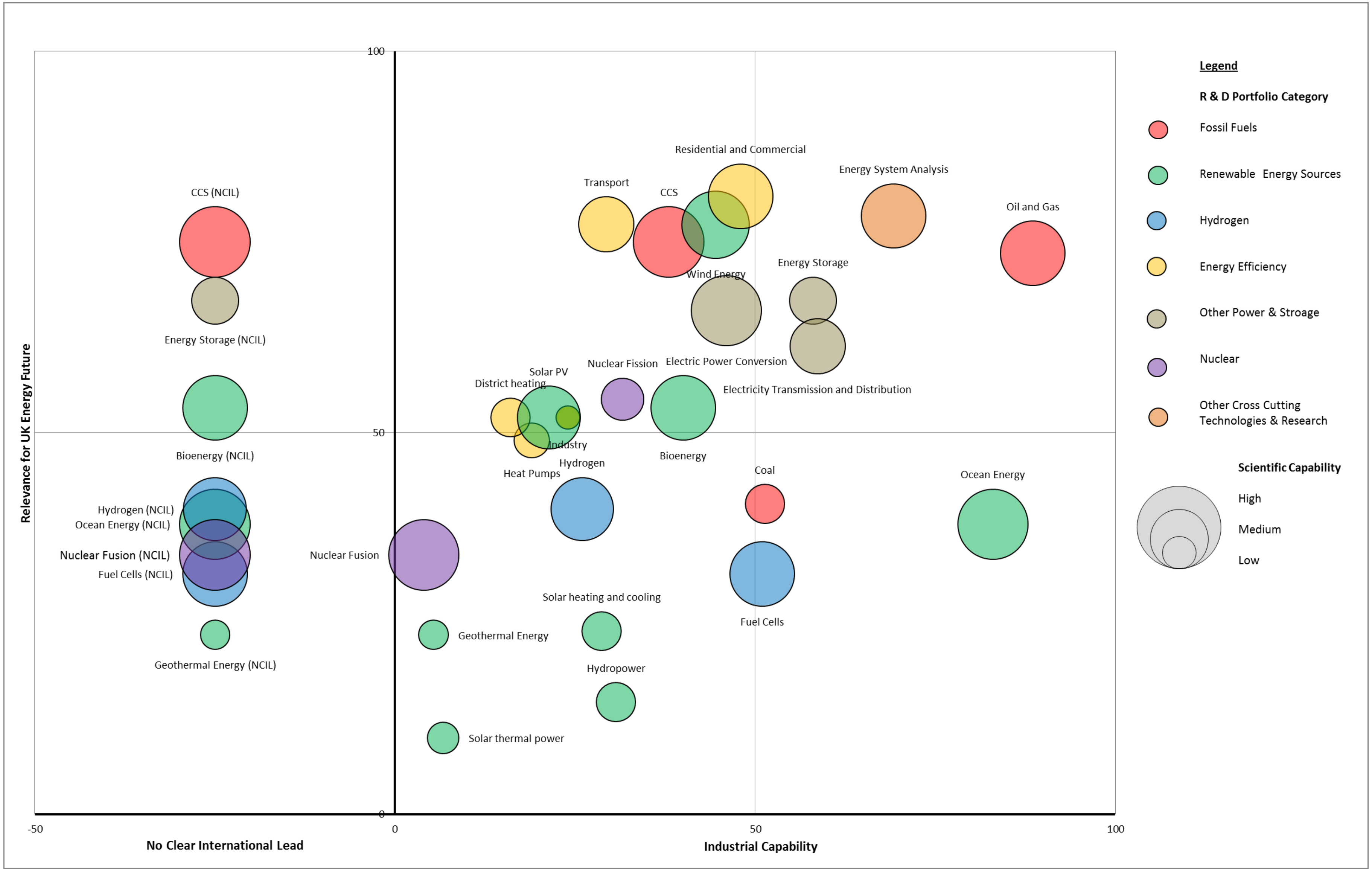

Figure 3: The UK's current and future energy R&D portfolio

3.3 Research Landscape Documents

The UKERC curates a set of 'landscape' documents, which map the research strengths, major academic and commercial research centres and large research programmes in a sector of energy research.

3.3.1 Solar PV

The UKERC Research Landscape 'Solar Energy'[14] lists the major research driver as the reduction of cost per watt of peak electricity, with the aim of making the cost per kWh generated competitive with fossil fuels. The major research challenges relate to both increasing the conversion efficiency of PV modules and reducing the manufacturing costs. There are also issues surrounding improving long-term reliability, especially with novel materials, as well as increased integration into the built environment. Materials sourcing, and finding more common replacement to rare and high-cost materials, is also important when considering large-scale manufacturing.

The UK is seen as active over all aspects of PV technology and across the supply chain, although capabilities can vary wildly between areas, with strengths broadly in materials science and weaker capabilities in manufacturing technology and process monitoring. Although PV manufacturing in the UK is facing very significant price pressures from China, the UK is in a strong position for early manufacture of new PV technologies such as dye-sensitised cells. The UK is overall seen as possessing a diversity of research strengths, but not achieving critical mass in any one area. This, however, makes the UK a competitive partner in the global collaborative research projects emerging in solar PV.

Table 1: UK's research capabilities in solar PV

High Capability	• PV Materials science; • Emerging technologies (organic solar cells); • PV System and components testing and installation; • PV module manufacture; • Architectural design; and • concentrated photovoltaics (CPV).
Medium Capability	• PV integrating system; • PV System and components performance monitoring; and • Equipment manufacture.
Low Capability	• PV cell design; • Power electronics; and • Process monitoring.

There are significant RCUK research programmes in solar PV and the current research portfolio, according to the Landscape document, is worth over £100 million including collaborative and underpinning research projects, accounting for around 8% of the RCUK Energy Programme budget. The £4 million SUPERSOLAR Solar Energy Hub programme, led from Loughborough University, is designed to coordinate research activities, conduct cross-technology research and provide a focus for international collaboration. There are over 80 currently funded large research programmes by the Research Councils across the solar PV sector, with the vast majority funded by EPSRC.

[14] UK Energy Research Centre, **'Research Landscape: Solar Energy'**, 2013, http://ukerc.rl.ac.uk/Landscapes/Solar.pdf

Applied and industrial research has been growing steadily in the UK, with growth of both small and medium enterprises (SMEs) and large investments from corporate buyers. The TSB and Carbon Trust are the key public funders supporting research projects at this stage, with substantial investments from private sector players and the EU Framework Programme 7 (FP7) programme. The UK is a member of the European Energy Research Alliance (EERA) Solar PV Joint Programme, designed to constitute strategic connections between European universities and technology centres.

3.3.2 Fuel Cells and Hydrogen

UKERC has two landscape documents covering this area: 'Fuel cells'[15] and 'Hydrogen'[16]. Key research challenges in the fuel cell sector relate to reducing costs while demonstrating reliability and durability in fuel-cell systems in real-world applications. Cost reductions are being investigated from several vectors – new materials, optimising engineering methods and innovative designs of systems and components.

Table 2: UK's research capabilities in fuel cells

High Capability	• FC materials science and engineering; • Cell and stack engineering; • Fuel processing; • System engineering; • Selected balance of plant components; • Fuel cell manufacture; and • Techno-economic modelling.
Medium Capability	• System demonstration; • Control systems; and • Power electronics.
Low Capability	• Product Trials.

There is substantial research activity in the UK in the fuel cells sector, building on a long history of experience in this area. The EPSRC currently support 36 research grants in fuel cells at UK universities, worth a combined total of £32.4 million. Of this total, four large grants have a combined value of £16.6 million, these being the Supergen on fuel cells, the Supergen on biological fuel cells, and the new Supergen Hub for hydrogen and fuel cells, which preforms coordination and partnership activities with a wide range of industrial and governmental stakeholders in addition to its core research activities. There is also a Centre for Doctoral Training (CDT) on hydrogen, fuel cells and their applications. There has been significant public support from TSB and the ETI for fuel-cell applied research and demonstration programmes, and several spin-out companies have emerged from UK universities, the most significant being Ceres Power, which develop solid-oxide fuel cells. Larger industry members also operate in this space and there has been some international interest, with Rolls-Royce Fuel Cell Systems being acquired by LG in 2012.

[15] UK Energy Research Centre, **'Research Landscape: Fuel Cells'**, http://ukerc.rl.ac.uk/Landscapes/Fuel_Cells.pdf

[16] UK Energy Research Centre, **'Research Landscape: Hydrogen'**, http://ukerc.rl.ac.uk/Landscapes/Hydrogen.pdf

The landscape document on hydrogen specifies the key challenge facing hydrogen in the UK as the need to investigate the whole-system viability of a hydrogen economy, in order to assess whether it can compete with and displace incumbent fossil-fuel technologies. Significant technical challenges include the development of compact hydrogen storage systems for use on-board vehicles and development of sustainable bulk hydrogen production pathways.

Table 3: UK research capabilities in hydrogen

High Capability	• Hydrogen production (dark fermentation); • Materials for hydrogen storage (metal hydrides; complex hydrides; porous materials); • Renewable energy systems; and • Socio-economic analysis.
Medium Capability	• Materials for hydrogen production; • Hydrogen production (other); • Hydrogen storage (devices); and • Hydrogen distribution.
Low Capability	• Hydrogen infrastructure; • Hydrogen systems; and • Reversible fuel cells.

EPSRC currently supports 34 research grants that investigate hydrogen as an energy vector, although inevitably this number considerably overlaps with fuel cell grants. The £4 million Supergen Hub for hydrogen and fuel cells consolidates previous hydrogen and fuel cell Supergen consortia, replacing in 2012 two previous Supergen grants on sustainable hydrogen energy, concentrating on hydrogen storage, and delivery of sustainable hydrogen, focusing on hydrogen production. Further hydrogen projects are funded directly under EPSRC's responsive mode.

The current responsibility for demonstration funding for hydrogen resides largely with the DECC, in conjunction with the TSB. Currently, five demonstration projects are being funded under the DECC-TSB 'Accelerating the introduction of fuel cells and hydrogen energy systems' banner. These include the UK's first end-to-end hydrogen production, distribution and retailing system, solar-hydrogen generation system demonstrations and wind-hydrogen electrolysis.

3.3.3 Energy Storage

The UKERC Landscape document 'Energy Storage' covers this area[17]. The UK has strong capabilities in battery development, with a focus on lithium batteries, as well as significant capabilities in redox flow batteries, supercapacitors and flywheel kinetic storage. Key challenges in this area are to improve the performance of storage solutions in terms of energy density and charge/discharge rates, make storage technologies more economical by lowering costs and to improve the operating lifetime of energy storage units through research into new materials and manufacturing methods.

[17] UK Energy Research Centre, **'Research Landscape: Energy Storage'**, http://ukerc.rl.ac.uk/Landscapes/EnergyStorage.pdf

Table 4: UK research capabilities in energy storage

High Capability	• World-class expertise in materials science, lithium battery technology, liquid and solid polymer electrolytes; • Historical expertise and development of flow battery technology; and • Historical expertise and development of flywheels with high-speed composite rotors.

EPSRC has identified storage as a priority area for research, and currently fund 17 grants totalling £8.7 million. The largest of these are the Supergen energy storage consortium, funded until 2014 at a total of £3.39 million, and the Transport Grand Challenge 'Crossing the Boundaries of Energy Storage' totalling £3 million. Most grants focus on materials research for batteries and redox flow cells. More applied R&D is funded by the TSB, ETI and Carbon Trust, with the TSB launching in 2012 an energy storage technology demonstration competition with a budget of up to £17 million, aimed at small businesses looking to develop and demonstrate pre-commercial grid energy storage systems.

Energy storage has been identified by the Department for Business, Innovation and Skills (BIS) as one of the 'eight great technologies' important to the UK's future growth, and was awarded £30 million in January 2013 to create dedicated R&D facilities to develop and test new grid-scale storage technologies.

3.4 Expert Workshop

Participants at the Expert Workshop were asked to score on a scale of 0-10 how well they thought the UK was now in terms of research capabilities for tackling future challenges in electrochemical energy and energy storage. The average score of the participants was 5.6 (±2.2), with 27% of participants giving the UK a high score (7-10), 53% giving a medium score (4-6) and 20% giving a low score (0-3).

This represents a distributed and somewhat lower set of scores than many of the other workshops. A very strong theme emerging from the comments around this exercise 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.

4. Existing roadmaps and innovation needs assessments

This section explores existing roadmaps and assessments in the electrochemical sector, and aims to highlight priority research challenges emerging from these documents. Documents covered include publically available roadmaps and assessments, as well as technology innovation needs assessments (TINA), compiled by the Low Carbon Innovation Coordination Group, where appropriate.

4.1 Solar PV

A number of solar PV development and deployment roadmaps exist both on a country-by-country basis and on a global scale. The rapidly dropping price of PV modules in recent years has presented difficulties for roadmaps, due to cost reductions outstripping even optimistic forecasts of PV prices.

UK

Several roadmaps have been produced by industry and trade associations for solar PV research and deployment in the UK, of which the most recent is the **UK PV Roadmap 2013**, authored by the Centre for Solar Energy Research at Glyndwr University in conjunction with the Electronics, Sensors and Photonics Knowledge Transfer Network. This states that the UK research and industrial community possesses considerable strengths in many elements of the PV supply chain and is well placed to significantly increase its market share, with the roadmap estimating a 10% global market share if strategic recommendations are followed. The UK has significant strengths and expertise in instrumentation, devices and in-line production tools, and should concentrate on becoming a global leader in these services, while retaining ambitions to expand to cover more of the manufacturing chain.

The roadmap identifies six priority areas, each with three key actions, to achieve increased deployment of UK products locally and globally and a sustainable UK PV market. These areas range from manufacturing to grid integration, policy and public perception, and are recommendations for industry and government as well as academia. The priority areas are listed below, with key actions within the scope of this prospectus listed under their respective headings.

Module Technology and Manufacturing:

- Building integrated PV (BIPV): Raising awareness of products and value, developing bespoke materials for BIPV.
- Manufacture: Up scaling of manufacturing technologies through proof of concept and new sustainable materials.
- Commercialisation of UK R&D: Strengthen links between industry and academia through collaborative R&D funds, applied R&D collaboration within the UK and generally enhance innovation profile and licensing opportunities in the UK resulting from strong collaborations.

Grid Connection and Infrastructure

PV Installations

Product Confidence and Reliability:

- Accredited testing facility for components and systems, microgeneration certification scheme (MCS) with more credibility (Gold, Silver, Bronze), NVQ;
- Appropriate standards and tests for long term environmental impact and stability; and
- Real world testing and demonstration facilities established for novel products.

Public Perception, Education and Training:

- Shift to multi-disciplinary skills training to encompass: communication, electrical system design, aesthetics and how we use energy.

Policy

The roadmap makes recommendations across the research, development and demonstration (RD&D) chain in the UK, including recommendations in deployment, policy and regulation activities. Research recommendations include greater unification of research and industry by developing a single, large and accredited PV research centre, as well as government investment and policy to strengthen the links between industry and research. The roadmap also calls for greater emphasis on training, in research and industry, with a need to up-skill the workforce across the value chain. The establishment of some PV grand challenges focusing on lowering embodied energy was recommended as a way to build a greater UK manufacturing industry, producing modules with lower embodied energy compared to imports.

There is currently no TINA document covering solar PV. DECC are currently producing a UK Solar Strategy in conjunction with industry, with publication expected before the end of 2013.

EU

The European Industrial Initiative (EII) on Solar Energy developed a strategic research roadmap and corresponding implementation plan in 2011 under the Strategic Energy Technology (SET) Plan.[18] It provides a detailed overview of the research challenges in each PV technology area over the near-to-medium term. Research topics common to all technologies are:

- Efficiency, energy yield, stability and lifetime;
- High productivity manufacturing, including in-process monitoring and control;
- Environmental sustainability; and
- Applicability, standardisation and harmonisation of PV modules.

The associated Implementation Plan[19] provides details on implementation, collaborative working and training, with recommendations for coherent Member State research programmes that stay abreast of other Member States' findings and optimal use of research infrastructure across the EU, including the upgrading of infrastructure lines to stay up-to-date with demand. There are other technological sectors that intersect with PV RD&D work, including material manufacturing, printing and organic electronics, automation and informatics; these should be able to contribute knowledge and experience through Technology Platform programs.

Global

The IEA produced a technology roadmap on solar PV energy in October 2010[20]. This roadmap, largely a deployment roadmap but with significant sections on R&D efforts, was informed by a number of existing roadmaps from the EU, US, China, Japan and others and projects that PV will provide 11% of global electricity consumption under the roadmap vision. The roadmap considers the range of existing and emerging PV technological solutions and provides technology development and R&D goals as well as regulatory and market recommendations to incentivise the adoption and support of PV technologies.

Significant cost reductions (0.5 years pay-back time by 2050) and efficiency improvements (up to 40% by 2050) are the two major strategic goals of the roadmap, along with continuing research efforts in a wide range of PV technologies. Specific technology goals and R&D issues raised by the roadmap include:

Crystalline silicon technologies. Research challenges include; new silicon materials and processing, improved device structures, cell contacts, emitters and passivation, productivity and cost optimisation in production. Continuous targeted R&D efforts in this area with a near-term focus can result in substantial cost reductions and an associated volume effect, which are needed to enhance competitiveness and accelerate the scaling-up of PV in the next decade.

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18 Solar Energy EII, **'A Strategic Research Agenda for Photovoltaic Solar Energy Technology 2nd Edition'** 2011, http://www.eupvplatform.org/publications/strategic-research-agenda-implementation-plan.html

19 Solar Energy EII, 'Today's actions for tomorrow's PV technology', 2009, http://www.eupvplatform.org/publications/strategic-research-agenda-implementation-plan.html

20 IEA, **'Technology Roadmap: Solar photovoltaic energy'** http://www.iea.org/roadmaps/

Thin films. Research challenges include; improved substrates and transparent conductive oxides, large-area deposition processes, improved cell structures, improved deposition techniques and advanced materials and concepts. Increased R&D efforts in this area are needed to bring thin-film technologies to market and to create the necessary experience in industrial manufacturing and long-term reliability.

Emerging technologies and novel concepts. This area comprises advanced inorganic thin-film cells as well as organic solar cells. Research challenges include; super high efficiency cells (over 45%), low cost high-performance solution for optical concentration and tracking, improvement of efficiency and stability for initial commercial applications, proof-of-principle of new conversion concepts and processing, characterisation and modelling of nano-structured materials and devices. Novel concepts in PV require considerable basic and applied R&D efforts in the mid- to long-term to further develop these concepts and to ultimately bring them to market.

The IEA makes some generalised recommendations for solar PV research, grouped into short- (S), medium- (M) and long- (L) term recommendations.

- Improve the technical performance and cost-efficiency of solar cells, modules, and system components, both for existing as well as for new solar cell technologies (S-L).
- Improve manufacturability of components and systems for industry-scale production with substantial mass production and cost reduction potential (including manufacturing plant demonstration) by utilising economies of scale and scope (S).
- Design PV as a building material and architectural element that meets the technical, functional, and aesthetical requirements and cost targets (S-M).
- Develop emerging technologies and novel concepts with potentially significant performance and/or cost advantages (M-L).
- Apply life-cycle assessments and optimise the environmental impact of PV systems (M-L).
- Develop and implement recycling solutions for the various PV technologies (S-M).

The roadmap states that RD&D efforts in solar energy need to increase by a factor of between two to four in order to achieve their BLUE Map 2050 goals of a global 50% reduction in CO_2 emissions. Greater international collaboration, particularly with developing economies, is recommended. The report also makes recommendations for policymakers to provide long-term stable targets and supporting incentive policies to support development and capacity building. Training and education efforts to support workers along the value chain are also important.

4.2 Fuel Cells and Hydrogen

UK

The UK Fuel Cell Development and Deployment Roadmap was published by Fuel Cells UK (now the UK Hydrogen and Fuel Cell Association)[21]. It highlights five key steps to be taken to promote fuel cell R&D in the UK:

- **Achieving high level political buy-in.** This will help to ensure that potential policy benefits are fully realised. Action by industry and Fuel Cells UK is needed to stimulate strong political commitment.

[21] Synnogy, 'UK Fuel Cell Development and Deployment Roadmap', 2005, http://www.ukhfca.co.uk/wp-content/uploads/2009/04/uk-fuel-cell-roadmap.pdf

- **Supporting fuel cell R&D.** Funding of the order of £10-20m per year is needed if UK R&D capability and effort are to realise their potential to deliver policy objectives, and to support the growth of the industry.
- **Establishing a Fuel Cell Coordination Group within Government.** The Group's role would be to harmonise and unite relevant policies and initiatives, thus facilitating a streamlined and efficient approach to support for the development and deployment of fuel cells in the UK.
- **Fostering significant UK deployment of fuel cells**. The early trial and medium term demonstration of fuel cell applications can help to optimise the technology, encourage the development of supply chains, improve awareness and understanding and, at significantly large scale, help to bring down costs and kick-start mass markets.
- **Introducing a forward public commitment to buy**. Forward commitments by public sector procurers offer a powerful mechanism for the market to deliver innovative solutions to meet policy needs.

The UK H_2Mobility consortium, which was set up to determine how to enable commercial deployment of hydrogen fuel cell electric vehicles (HFCEVs) in the UK, has outlined a roadmap[22] towards deploying fuel cell electric vehicles FCEVs in the UK as quickly as possible from 2015, when they are expected to be available on the international market. This roadmap is geared heavily towards deployment, with sections on consumer demand, market introduction and retail processes, with detailed research requirements to come in a future Phase II.

There are currently no TINA documents covering fuel cells or hydrogen, though a TINA covering hydrogen is currently in development.

EU

The document 'Fuel Cell and Hydrogen technologies in Europe 2014-2020[23]' covers RD&D efforts in these technologies in the EU in the near-term. It recommends substantial expansion in public-private partnerships in this area, following the model of the Fuel Cell and Hydrogen Joint Undertaking (FCHJU), which has implemented a €940 million programme up to 2013 with a 50:50 public-private funding split. They recommend a substantial increase in investment in this area up to 2020, with two major focuses: improving the competitiveness of technology solutions and increasing the share of renewable sources in the hydrogen production mix. The roadmap lists the following major technology objectives:

- **Hydrogen Production and Storage**. Reach H_2 delivery cost/kg at point of use at a competitive cost compared to fossil fuel solutions in 2020, excluding taxes.
- **Transport applications**. Demonstrate competitive Fuel Cell Electric Vehicle (FCEV) and infrastructure solutions.
- **Stationary Applications**. Demonstrate the economic viability of the use of fuel cell technologies for providing electricity and heat for residential and industrial needs for the following market segments.
- **Early Market Applications.** Make fuel cells a visible and a competitive technology option in early market applications.
- **Regulation, Codes & Standards (RCS), Pre-normative Research and Societal Acceptance**. Ensure common standards are approved and applied throughout Europe within a positive societal acceptance of the technologies.

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22 UK H2Mobility Consortium, 'Roadmap: Phase 1 Results', 2013, http://www.ukh2mobility.co.uk/wp-content/uploads/2013/08/UKH2-Mobility-Phase-1-Results-April-2013.pdf

23 NEW-IG,**' Fuel Cell and Hydrogen technologies in Europe 2014-2020'**, 2011, http://www.fch-ju.eu/sites/default/files/111026%20FCH%20technologies%20in%20Europe%20-%20Financial%20and%20technology%20outlook%202014%20-%202020.pdf

Other actions recommended include a coherent technology framework, similar to the EIIs, to monitor progress towards the objectives of the FCH-JU.

Global

An IEA roadmap covering hydrogen is in development for expected release in 2014. No IEA roadmap specifically covering fuel cells is currently in development.

The US Department of Energy has published a Strategic Plan for fuel cell and hydrogen RD&D[24]. This reviews the Hydrogen and Fuel Cells Program, which supports this area from basic research through to demonstration and validation. This identifies several barriers to the commercialisation and uptake of hydrogen technologies and fuel cells, including cost, durability, an inadequate manufacturing and supplier base, inadequate workforce skills and a lack of investment in infrastructure.

The plan implements increased R&D efforts in materials and systems, to achieve lower-cost and higher performance fuel cell systems and components for hydrogen fuel production and storage. Safety R&D efforts, to develop hydrogen sensors, codes and standards and safe working practices, are also planned.

Japan's fuel cell and hydrogen RD&D efforts are led by the New Energy and Industrial Technology Development Organisation (NEDO), under the auspices of the Ministry of Economy, Trade and Industry (METI). Japan's major automotive manufacturers have agreed on a commercialisation date of 2015 for HFCEVs, and early commercialisation efforts, including infrastructure expansion, will begin at that time.

4.3 Energy Storage

Roadmaps and need assessments for grid-scale energy storage systems are difficult to come by, due to the wide range of technologies in this area. It is useful to discuss storage as a range of different components, of which the most RD&D effort is currently going into battery technologies. The general aims in these technologies are similar to those found in the fuel cells area, increasing energy density and conversion efficiency while reducing cost and weight. The European Commission Directorate-General for Energy EC DG-Energy) Working Paper 'The Future Role and Challenges for Energy Storage'[25] lists the main challenges to adoption of grid-scale energy storage as technological; both increasing capacities of existing technologies and developing new, more efficient solutions; market and regulatory issues and strategic issues, involving considering storage as a holistic part of the energy system.

The TINA document 'Electricity Networks and Storage'[26] covers this area, and is partially discussed in **Prospectus Report 10: Energy Infrastructure.** The document estimates that innovation in energy storage technologies could potentially yield total system cost savings of £5 billion in the period to 2050. The TINA identifies several select storage technologies which offer the most potential, including thermal-to-electric storage, lithium-based batteries, sodium-based batteries, and redox flow batteries. Critical market failures and barriers identified for storage technologies include:

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[24] US Department of Environment (DOE), 'An Integrated Strategic Plan for the RD&D of Hydrogen and Fuel Cell Technologies' 2011, http://www.hydrogen.energy.gov/roadmaps_vision.html

[25] EC DG-Energy, 'The Future Role and Challenges of Energy Storage', http://ec.europa.eu/energy/infrastructure/doc/energy-storage/2013/energy_storage.pdf

[26] Low Carbon Innovation Coordination Group, 'Technology Innovation Needs Assessment: Electricity Networks and Storage', 2012, http://www.lowcarboninnovation.co.uk/working_together/technology_focus_areas/electricity_networks_storage/

- All parties – including regulators, network operators, and technology providers – are unsure of the value and the extent of the role storage will play in the future energy system, creating a barrier to innovation and deployment.
- The value of some of the services that storage can provide, such as voltage support or transmission and distribution investment deferral, cannot be easily captured under existing market arrangements.
- Lack of clarity about infrastructure planning, particularly development of infrastructure that could substitute for storage technologies, does not give parties sufficient confidence to invest in R&D or deployment.

Storage technologies were identified by the TINA as being an area with high relative benefit from UK public sector activity and investment, with high values in meeting emissions targets, green growth potential and the high possibility of critical failures without public support. The TINA however recommends public support is concentrated on a select few key technologies to avoid duplicating other countries' efforts. Thermal-to-electric storage, redox flow batteries and novel pumped hydro were considered to represent unique UK strengths, and large-scale RD&D efforts, on the scale of tens of millions of pounds were recommended to pursue RD&D activities in these areas. Continued strong efforts were also recommended for improved lithium-based and sodium-based batteries, focusing on improving durability, lifetime and cost.

There are several roadmaps covering developments in lithium-ion batteries for mobility – these are covered to an extent in **Prospectus Report 4: Transport Energy'**. The Fraunhofer Technology Roadmap for[27] covers the period up to 2030, providing an indicative roadmap for the development of lithium-ion batteries and replacements including lithium-air and sodium batteries.

5. Research Challenges

The research challenges identified in the expert workshop were divided into three broad application areas by the workshop participants:

1. Photovoltaics
2. Fuel Cells and Hydrogen;
3. Batteries and other technologies; and
4. Broader issues and underpinning challenges.

There are underpinning challenges in environmental, economic and political issues that cut across these three application areas.

[27] Fraunhofer ISI, **'Technology Roadmap Energy Storage for Electric Mobility 2030'**2011, www.isi.fraunhofer.de/isi-media/docs/t/en/TRM-ESEM-2030_en_web.pdf

Table 2: Research Challenges in the area of PVs

Challenge
PV and hybrid system integration
New materials for PV devices
Low-cost manufacturing for new PV technologies
Low-cost, high efficiency PV cells
New materials for photon capture
Improving the supply chain for PV modules
Scalable, low-cost thin film deposition methods
Thin film materials which are stable over a long period of time
Transitioning from bolt-on to building-integrated PV

Table 3: Research Challenges in the area of Fuel Cells and Hydrogen

Challenge	Notes
Fundamental understanding of materials and interfaces	
Understanding degradation of catalysts and membranes over time	
Durable technologies: need to last for at least a decade of operation	
New materials for catalysts and electrodes	Including finding more abundant alternatives to rare-earth and platinum-group metals
Implementing hydrogen as a sustainable energy vector	Technologies for producing, storing and transporting hydrogen economically at scale
Substantial cost reductions in materials and manufacturing	
Life-cycle energy cost analysis	
Methods to measure and understand the performance of the device whilst in operation	

Table 4: Research Challenges in the area of Batteries and Other Technologies

Challenge
Thermal Storage: Improved materials and lower costs
Lossless capacitors for short- and medium- term charge storage
Hybrid batteries/ supercapacitors to provide
Understanding appropriate energy storage technologies over different timescales and capacities
Development of lithium-air and metal-air batteries
Modelling to improve understanding of integrating hybrid systems
Researching degradation issues to improve the lifetimes of electrochemical devices

Table 5: Broader Issues and Underpinning Challenges

Area	Challenge	Notes
Environmental impacts and ecosystem services	Sustainability challenges	There is a need for abundant, green alternatives to many currently-used materials in this sector
Economics and social science	The need for long-term political and economic support	Long-term perspective and support is needed to bring many of these technologies to market
	Cost reduction	A need to reduce cost and increase performance exists for the majority of technologies in this sector
	User behaviour and demand	Tailoring and designing products to consumer needs, desires and abilities

6. Research Conduct

This section draws on the Expert Workshop sessions to identify actions which the research community, the Research Councils and others could take to improve research coherence, conduct, infrastructure and skills training in this area.

6.1 Ways of Working

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.

Reproducibility. 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. There could be an incentive scheme to check published results in order to ensure regular and rigorous checking of published findings.

Strategic Framework. A strategic framework for the electrochemical area would be useful to establish major challenges, identify areas of cross-collaboration between research groups, and provide a simple overview of the area, allowing collaborative efforts to be identified more easily.

More risky 'blue-skies' research. Basic research into new phenomena and materials, often known as 'blue-skies' research due to the lack of any identifiable applied benefits, is risky but very important for this sector, as it has the potential to find transformative breakthroughs. This research should continue to be funded and increased in quantity in order to provide an excellent base of new basic research in this sector.

6.2 Long-term perspectives

Political support and long-termism. 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. To match international competitors, a long-term vision and associated support is required. Research priorities should be decided on an apolitical basis, and linked more directly to longer-term forecasts and the 2050 goals.

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.

6.3 Data

User-accessible fast computers. Materials research requires complex molecular modelling and simulations. These would be best handled by investing in fast, powerful and cheap computers, which would ideally be user-friendly to allow non-experts in computing to access these models and research capabilities.

Databases. Databases to collect and share data on properties of materials and interfaces and test results of devices were proposed, either centrally- or user- curated. These would be accessible by the UK research community, and would facilitate more open sharing and collaboration. There are some issues around intellectual property (IP), particularly in device testing, which may need complex arrangements to access.

6.4 Infrastructure and facilities

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.

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.

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.

Increased availability of Science and Technology Facilities Council (STFC) facilities. STFC has world-class facilities for research and analytical techniques, which need to be maintained and availability to researchers increased. There will be an increasing need, and therefore operational time, for these facilities in the future as industrial challenges increase in difficulty and require smaller-scale analysis.

7. Training

Sustainable career paths. There should be opportunities for researchers to follow career paths that are sustainable, offer significant development and can lead them through their career from undergraduate to professor. This would allow promising new researchers to enjoy greater career certainty, and could attract good candidates from industry. Starting salaries in UK academia are also low compared to competitors. Starting salaries average about 70% higher in the US and Australia, which hinders recruitment of good candidates.

PhD funding models. As in all areas of energy research, there is opposition to the exclusive use of the CDT model in delivering PhD training. While the CDT model is a good one, it is believed that it has led to a big gap in the supply of trained people. A system where CDTs are complemented by project and discipline-based studentships would be more appropriate. Some also believe that an additional taught year is unnecessary for all students, some of whom could move straight into research PhDs.

Transferable skills. PhD training should be designed so that the skills attained can remain relevant even if the industry radically changes. A balance between the acquisition of deep skills and wider transferrable skills is needed.

Industrial Collaborative Awards in Science and Engineering (CASE) awards. These were seen as a useful way to bridge the gap between academia and industry, as well as providing a way for project-specific PhD students to be funded.

8. Making connections

8.1 Linkages outside RCUK

Partnership between academia and industry – knowledge sharing. Knowledge of the potential applications of electrochemical technologies and 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 improve knowledge sharing?

More active engagement from DECC and BIS. DECC and BIS are the government departments charged with running and evolving the energy system. They should be more engaged with the direction of research challenges in this area, as widespread usage and adoption of commercialised electrochemical technologies such as PV, fuel cells and storage have the potential to change the energy system in significant ways.

Handing research models to industry. More joint or joined-up research with industry in the modelling area would be fruitful. Closer collaboration, including the handing over of research models to industry, could accelerate the development of new materials in commercial products.

8.2 International working

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? Research into advanced manufacturing could be more lucrative than assembly, especially if future manufacturing capabilities can be highly flexible.

Greater international engagement. The UK research community should ensure that it engages with and is integrated with key programmes in other nations. Programmes such as the EERA and the FCH-JU should be engaged with fully to ensure UK research is not duplicating work done elsewhere in the EU, to take advantage of upcoming Horizon 2020 bids and to more fully feed UK research efforts into EU policymaking. Key programmes in the US, East Asia and India should also be identified and interacted with.

8.3 Public engagement

Public interaction to increase the profile of electrochemical technologies. The general public currently treat energy as passive consumers, whereas most electrochemical technologies will require them to become more active participants in order to maximise the utility of the technologies. Educating the public, perhaps through long-term methods, on what fuel cells, the hydrogen economy and energy storage are, why they are useful and how they could reduce CO_2 emissions could greatly aid policy and deployment efforts.

9. Conclusions and Recommendations

This prospectus report covers a wide-ranging cross-section of technologies and innovations. Solar PV, fuel cell technologies, the wider hydrogen economy and energy storage technologies each have the potential to change the energy system both globally and in the UK drastically. The scope of this report also covers a greater quantity of physical science work than in other areas of energy research. Basic research in physics, chemistry and materials science directly feeds in and helps develop these technologies, and such 'blue-sky' research is important in ensuring the UK attains and keeps a competitive edge in these areas. A strategic framework for the electrochemical area would be useful to establish major challenges, identify areas of cross-collaboration between research groups, and provide a simple overview of the area, allowing collaborative efforts to be identified more easily.

In many cases, the technologies and research described in this report will not reach technological maturity for years or decades. Long-term support for this research is thereby important in ensuring that the UK will gain the eventual benefits from this work. The UK's major international competitors often have long-term visions backed up by strategic road-mapping and apolitical support, and similar moves towards long-term planning will help the UK remain internationally competitive in these fields.

A strategic framework for this area would be useful to establish major challenges, identify areas of cross-collaboration between research groups, and provide a simple overview of research efforts, allowing collaborative efforts to be identified more easily.

Test facilities and infrastructure are essential in ensuring innovations can progress from basic laboratory prototypes to demonstration products. This was seen as underfunded in the UK, and investment at this stage should be seen as important. Ensuring that researchers can gain timely access to STFC's analytical facilities and infrastructure is also key in this area.

To maximise success in developing and commercialising technologies of this nature, linkages between academic researchers and industry should be made very early in the research process. Joint and joined-up research with industry, particularly in areas such as materials modelling, could accelerate the development process.

There should be opportunities for researchers to follow career paths that are sustainable, offer significant development and can lead them through their career from undergraduate to professor. This would allow promising new researchers to enjoy greater career certainty and could attract good candidates from industry.

PhD training should be designed so that the skills attained can remain relevant even if the industry radically changes. A balance between the acquisition of deep skills and wider transferrable skills is needed. Centres for Doctoral Training should be supplanted by project- and discipline-based studentships where appropriate. Industrial CASE awards should be pursued and extended where possible.

Databases of results and properties of materials should be made available to the community, either centrally curated or user curated with a centralised index. Support should be provided to resolve IP issues where applicable.

Annex A: Research needs

These research needs come from detailed discussion sessions held during the Expert Workshop, and represent 'hotspots' of research that were seen to be necessary in the short- to medium-term to answer the research challenges in Section 5.

PVs

PV system integration

- Developing non-disruptive building-integrated PVs;
- Durability as part of a system – developing aging tests; and
- Developing multi-functional materials – shading, cooling, colours, and structural and aesthetic appeal.

New Materials for PV devices

- New materials for photon capture;
- Scalable materials synthesis for new materials and nano-materials;
- Development of PV materials which are stable, printable, earth-abundant and/or non-toxic;
- Materials durability and safety;
- Durable materials;
- Standards and quality assurance for new materials; and
- Life cycle assessment for new materials to determine which have high net energy yields.

PV modules and manufacturability

- Identifying materials and manufacturing bottlenecks in emerging PV technologies
- Developments in module engineering
- Addressing issues in safety, durability, standards and quality assurance
- Maintaining efficiency ratings in in the scale-up from laboratory to large-scale production
- Developing a UK repository of standard testing protocols and results for new materials
- Rapidly scalable manufacturing processes for new PV technologies.
- Improving aesthetics and installability of PV modules during the manufacturing process.

Fuel Cells and Hydrogen

Materials and Interfaces in Fuel Cells

- Molecular modelling and simulations of ion transport and interfaces.
- Translating molecular modelling into experimental measurements.
- Improved proton-exchange membrane (PEM) fuel cell membranes: less sensitive to hydration.
- New techniques and devices for studying interfaces under operating conditions.
- Understanding links between materials, production and quality assurance to operational reliability.
- Understanding mechanisms of degradation in fuel-cell devices.
- Improving the tolerance of solid-oxide fuel cells to fuel impurities.
- Understanding ion transport in materials – dynamics, interface and structure.
- Need for more efficient cathodes for low-temperature solid-oxide fuel cells.

- Non-nickel electrodes for solid-oxide fuel cells.
- Fuel cell materials and new electrolytes to enable operation between 200-500°C
- Developing process routes to enable recycling of high-value materials from electrochemical devices.
- Improved focus on materials and systems which have a good chance of increasing conversion efficiency.
- Research into H+ and OH- polymers: which category is better to focus efforts on?

Implementing hydrogen as a sustainable energy vector

- The electrolysis of unpurified water at natural pH.
- Methods of sustainable hydrogen production: PV- or wind-powered electrolysis, PV water-splitting, artificial photosynthesis.
- High-capacity hydrogen storage for vehicles
- Investigating the consequences of using the hydrogen gas grid for transportation, including the possible embrittlement of pipelines.
- Massive-scale/long-term hydrogen storage in geological structures or mines.
- Research into producing hydrogen using algae.
- Utilisation of low-grade heat for electrolysis.
- Research into efficient uses for the oxygen released during the water electrolytic process.

Batteries and Other Technologies

Future Batteries

- Electrolyte stability and electrode structure for metal air batteries.
- Anode metal choices for metal-air batteries: is lithium the most suitable metal?
- Materials to enable safer large-scale lithium-ion batteries.
- Research into efficient magnesium-ion batteries.
- New materials and chemistries for flow-cell batteries, which have a long lifetime and are low-cost.
- Safer electrolytes for high-energy density batteries
- Remote-monitoring battery management systems
- Advanced manufacturing (for example 3D printing) for electrodes and membranes.

Capacitive Storage

- Fast charge-discharge capabilities
- Supercapacitors which are suitable for short-term load levelling.
- Increase the working temperature range of supercapacitors
- Improve the manufacturability of supercapacitors, particularly at large-scale.
- Research on greater fundamental understanding of electrode surfaces

Thermal Storage

- Low-cost thermal storage, with different materials covering all grades of heat.
- Improve the efficiency of cryogenic storage.
- Light-weight storage for low-temperature, low-grade heat.
- Utilising molten salts as a storage vector.

Broader Issues and Underpinning Challenges

Hybrid Technologies

- Dual-use of storage between transportation and the grid in vehicle-to-grid technologies;
- Hybrid battery-hydrogen vehicles
- Research into hybrids utilising complexity theory. Does hybridisation add stability and security as well as flexibility?
- Reversible fuel-cell/electrolysis devices
- Integration of PV and heating systems through long-term thermal storage
- PV integrated with local storage for night-time energy delivery.
- Algorithms for control systems and optimisation of fuel efficiency for hybrid systems.
- Communications protocols and standards to ensure components communicate properly.
- Effects of hybridisation on durability: research into components of hybrid systems to ensure they are as durable as one another.
- Multifunctional materials for hybrid systems.
- Modelling decoupled hybrid systems (for example offshore wind coupled to onshore storage).

Issues of Scale

- Research questions surrounding up-scaling of materials production: rare and complex materials need to be produced at scale.
- Predicting demand for technologies over long periods of time: important for attracting investment in large manufacturing plant.
- Long-term strategic road-mapping for technology development.

Sustainability Issues

- Research into removing and recycling scarce critical materials from products.
- Research into ways to measure and understand the total embedded energy and carbon emissions in a device.
- Improving the lifetime of devices through improving degradation rates of electrochemical components.
- Investigate the possibility of thin-film deposition methods for all electrochemical devices.
- Investigate the feasibility of moving from solvent-based to water-based manufacturing processes.
- Safety should be incorporated as an important performance criterion.

User Behaviour and Demand

- Ways to educate the public on energy storage technologies and their uses.
- Research into effective incentives and barriers to demand-side management (DSM) solutions.
- Understanding changing attitudes to asset ownership.
- Educating the public on the complexity of the energy system and its changing nature.

Annex B: Process for developing the prospectus

This Energy Research and Training Prospectus Report has been developed under the auspices of the RCUK Energy Strategy Fellowship which was established in April 2013. Fellowship activities leading the production of the Prospectus have gone through three phases.

Phase I (Spring –Summer 2012), **the scoping phase,** involved a comprehensive review of relevant energy roadmaps, pathways and scenario exercises in order to provide a framework for possible UK energy futures. Extensive consultation with stakeholders across the energy landscape was carried out in order to encourage buy-in and establish clearly the boundaries and links between the RCUK Prospectus and other products related more to deployment. One conclusion arising from the consultations was that linkage should be sought across the energy research domain and that consequently related topics linked by underlying research skills should be covered in single workshops during Phase II.

Phase II (Autumn 2012 – summer 2013), **the evidence-gathering phase,** relied heavily on workshops bringing the research community and stakeholders together round specific topics. Three 'strategic' workshops on **Energy Strategies and Energy Research Needs, The Role of Social Science, Environmental Science and Economics,** and **The Research Councils and the Energy Innovation Landscape** were held October-December 2012. Six expert residential workshops on **Fossil Fuels and carbon capture and storage (CCS), Energy in the Home and Workplace, Energy Infrastructure, Bioenergy, Transport Energy** and **Electrochemical Energy Technologies** were held January- June 2013. In addition, 'light-touch' activities were conducted in respect of: **Industrial Energy; Wind, Wave and Tide;** and **Nuclear Fission.** A final strategic level 'synthesis' workshop was held in July 2013. During Phase II, reports on each of these workshops were prepared and web-published following comments from participants.

During Phase III, (summer-autumn 2013), **the synthesis stage,** the workshops reports were 'mined' and combined with contextual information to produce the Prospects Reports which were put out for peer review. The Prospectus, including a hard-copy Synthesis Report, was launched in November 2013.

Annex C: List of prospectus reports

No 1	Investing in a brighter energy future: energy research and training prospectus
No 2	Industrial energy demand
No 3	Energy in the home and workplace
No 4	Transport energy
No 5	Fossil fuels and carbon capture and storage
No 6	Electrochemical energy technologies
No 7	Wind, wave and tidal energy
No 8	Bioenergy
No 9	Nuclear fission
No 10	Energy infrastructure