Investing in a brighter energy future: ENERGY RESEARCH AND TRAINING PROSPECTUS

NOVEMBER 2013

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 task has been 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 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. 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*. While the report draws on extensive consultations, the views expressed are those of the Fellowship Team alone.

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Executive summary and recommendations

This report is based on an independent review of energy research and training needs conducted through the Research Councils UK (RCUK) Energy Strategy Fellowship. The consultations, workshops and documentary analysis that support this report have provided a comprehensive overview of energy research activities supported by the research councils and the connections between these activities and other energy innovation bodies, industry and policymakers.

The report represents part of the response to the recommendation of the 2010 International Review Panel that "a fully integrated 'roadmap' for UK research targets be completed and maintained to allow all to know and understand what is considered essential to meet society's needs".

This report's findings are in five areas :

- It has gathered evidence strongly endorsing the portfolio approach to energy research taken by the RCUK Energy Programme.
- It has identified the roles that broad areas of energy research, e.g. in energy infrastructure or fossil fuels, can play in meeting economic and social needs, their contributions to energy and climate change policy, and the competitiveness and growth agenda.
- It has identified high-level research priorities within each of these areas and, in the supporting documents[1], more specific research challenges and questions.
- It has identified issues regarding the way research is conducted and supported, and the way connections are made across the energy innovation domain, offering recommendations for improving these.
- It has generated suggestions for the support of training, primarily at the doctoral level but also at the masters level, as well as recommendations to promote career development.

The report has generated a long list of recommendations. Like the International Review Panel, we have found it hard to ignore the wider context in which the research councils operate. Therefore, whilst some of our recommendations are aimed at the research councils specifically, others are relevant to the UK's energy innovation bodies more broadly. Consequently, our recommendations are categorised according to their focus: the wider energy innovation system; research councils more broadly; the RCUK Energy Programme; and topic-specific research questions.

From the recommendations, three issues stand out:

The level of financial support for energy innovation. This is well below the level commensurate with the UK's ambitious energy and climate change targets and would need to be raised considerably to bring it in line with our international peers.

Cross-council and interdisciplinary working. Although considerable progress has been made, much work remains to be done to establish suitable collaborative arrangements that satisfy the spirit of the International Review Panel's recommendation for "a single, well defined, cross-Councils' energy research budget with coordinated deployment mechanisms".

Communication and transparency. There is an on-going need to communicate the relationship between the research councils' Royal Charter objectives, their Strategic and Delivery Plans, and the specific choices that are made in supporting research and training activities. The logic behind the research councils' decision- making is not always understood by the research community.

The specific recommendations follow.

UK energy innovation system

1. Acknowledging public expenditure constraints, the research councils and other research and innovation bodies should press for public expenditure settlements that are better aligned with the UK's wider climate change and energy policy ambitions.
2. The research councils and other bodies should build on progress in coordinating energy RD&D across the innovation landscape by contributing to the effective operation of the Low Carbon Innovation Coordination Group (LCICG) and engaging in active collaboration through, for example, joint funding calls encompassing activity along the innovation chain.
3. The UK should exert greater influence over the development of EU programmes and attempt more co-ordination of programme involvement. The research councils should continue to support UKERC in leading the engagement of UK researchers in the European Energy Research Alliance (EERA) and Horizon 2020. LCICG could act as the focus for UK engagement with the EU and the International Energy Agency (IEA) more broadly. Effective co-ordination would require more resources than are currently allocated.

[1] See *http://www3.imperial.ac.uk/rcukenergystrategy/prospectus/documents* for access to supporting documents.

4. Ofgem's role in LCICG should be upgraded from associate to full membership given its role in stimulating energy network RD&D, which is having a significant impact on the research landscape. This would ensure better integration and help to facilitate an appropriate allocation of energy RD&D resources.

5. In reporting energy R&D activity for statistical purposes, UK energy research and innovation bodies should adopt, as far as possible, the EU/IEA energy R&D nomenclature to facilitate comparison both internationally and across organisations within the UK.

6. The Technology Readiness Level (TRL) concept, when it is used, should be applied with greater rigour than at present.

The research councils

7. In developing their Strategic Plans, the research councils should plan beyond the time horizons associated with budgetary cycles to enable long-term investments in infrastructure, surveys, trials and experiments to be exploited fully. Strategies should take account of long-term energy policy goals and associated uncertainties. Long-term plans should be flexible, should not be seen as establishing firm budgetary commitments and should be reviewed at regular intervals.

8. The research councils should be prepared to make selective longer-term research investments of 10 years or longer, subject to rigorous stage-gating procedures, where there is clear evidence that scientific benefits cannot be realised on shorter timescales. Examples include field trials for crops, cohort studies in the social sciences and the evaluation of the impacts of policy interventions.

9. The research councils should be more transparent about the blue skies/application orientation of their research support in specific areas and should consider adopting consistent approaches where different councils are supporting related topics.

10. The research councils should be more transparent about the way they prioritise research and select funding mechanisms. The logic behind many choices is not explained and the wider perception is that decisions emerge arbitrarily. There is a need to communicate better with the research communities about how decisions are framed by Strategic Plans and wider considerations.

11. The research councils should keep under review, through their participation in the Large Facilities Steering Group, the level of support for the operating budget of facilities to ensure that capital-intensive infrastructure is exploited appropriately. The Science and Technology Facilities Council (STFC) should consider how to balance continued support across all facilities against more intensive use of a more selective group of assets.

12. In the longer term, decisions about capital investments and operating budgets should be more closely linked. This could be achieved in part by adopting a life-cycle perspective when undertaking capital decisions and making provisional commitments for subsequent operating spend. These could then be the subject of on-going review.

13. The Biotechnology and Biological Science Research Council (BBSRC) and the Engineering and Physical Sciences Research Council (EPSRC) should consider establishing stronger data sharing policies and should identify or establish suitable repositories for data having manifest 'common good' characteristics. EPSRC should identify what types of data resulting from its support are priorities for curation and sharing.

14. Data on doctoral and masters programmes, including numbers and types of students and specific strategic shortfalls, should be collated in order to identify more clearly the current state of the area.

15. Research councils should establish a framework for public engagement that starts from the top and does not simply pass responsibility down to individual programmes and projects. Consultation and engagement over the development of Strategic Plans would provide a good starting point. Such engagement should explicitly address the degree to which stakeholder views may or may not be reflected in the development of research agendas so that realistic expectations are established. A high level framework could guide engagement processes at the programme and project level.

Research Councils UK Energy Programme

16. Energy R&D portfolios, especially those supported by bodies such as the research councils with a basic/strategic research remit with potential pay-offs in the long-term, should reflect significant uncertainties about the development of the energy system. It is not realistic to rely on the emergence of clarity regarding energy policy to guide research and training strategies.

17. Mechanisms for co-ordinating energy research across RCUK should be strengthened and greater use should be made of jointly commissioned research initiatives/consortia to respond further to the spirit of the International Review Panel's recommendation about a single well-defined energy research budget.

18. EPSRC, in its leadership of the Energy Programme, should be receptive to ways of framing energy research challenges that are derived from a wider range of disciplinary perspectives. At the same time, other councils should clarify how energy is positioned within their Delivery Plans and actively promote alternative framings within RCUK.

19. The communication of the cross-council RCUK Energy Programme should better reflect the potential contribution of all research councils. The Programme is often confused with the EPSRC energy theme. Other research councils could help by clearly identifying the contributions that their Strategic and Delivery Plans make to energy research.

20. The RCUK Energy Programme should continue to support ambitious interdisciplinary research initiatives.

21. The research councils, especially the Economic and Social Research Council (ESRC) and potentially the Arts and Humanities Research Council (AHRC), should consider how disciplines which have not traditionally contributed to energy research could be engaged. Putting in place a process for mapping out potential contributions would be a good starting point.

22. The research councils should consider establishing research networking/champion arrangements in areas of energy research to which particular priority is attached, where they have not done so already. Such arrangements have proved successful in areas such as nuclear and carbon capture and storage (CCS).

23. The research councils should note relevant connections between different research areas when planning new research investments, particularly in relation to the cross-cutting research themes of materials science, socio-economic issues and environmental science.

24. The 'best with best' principle should be implemented rigorously when developing international collaboration. International co-operation efforts could be selectively extended beyond the current group of priority countries on a topic by topic basis.

25. The research councils should adopt a more rigorous and precise approach to defining areas of energy research and, if possible, avoid terms subject to misinterpretation such as 'conventional' or 'sustainable' unless their meaning is well understood across the relevant research communities.

26. EPSRC funding models for PhD training could blend different approaches – Centres for Doctoral Training (CDTs), project-based, Engineering Doctorates - in a way that enables prospective students to choose the training experience that best supports their longer-term career aspirations. Any new model should include safeguards to embed students within a research community and prevent them becoming isolated. Other Councils could learn from EPSRC's experience in this respect.

27. The transferability of research skills should be considered so that people enjoy good employment prospects even if specific energy technologies do not achieve widespread deployment. CDTs might, for example, be structured around clusters of technologies that require similar skill-sets rather than individual technologies.

Topic-specific research recommendations

Industrial energy demand

28. 'Whole systems research' focusing on industrial energy systems, their wider role in the economy and links to materials flows should continue to be supported through collaboration between EPSRC and ESRC.

29. The case for directed support for industrial process energy research is relatively weak. EPSRC should provide support through broader manufacturing initiatives and responsive mode. The relevant research communities should be encouraged to take up these opportunities and establish suitable links with industrial partners.

Energy in the home and workplace

30. Building on recent research investments, the research councils need to continue directing resources towards building energy technologies, energy consumption behaviour and business models for energy supply. Given the socio-technical nature of the research challenge in the area of energy demand, it is important that research is sensitive to technical aspects, social aspects and their interaction.

31. A greater emphasis needs to be given to research aimed at understanding energy consumption in commercial environments..

Transport energy

32. Given the socio-technical nature of transport energy research challenges, it is important that interdisciplinary research be supported, covering technical aspects, social aspects and their interaction. Research challenges need to be formulated across a range of spatial scales to provide a stronger 'whole system' understanding of the transport energy system.

33. Research should focus not only on novel transport energy technologies and infrastructures but also on improving the effectiveness of existing ones.

Fossil fuels and CCS

34. The research councils should build on the UK scientific strengths and hedge against uncertainties concerning the future role of fossil fuels by investing in research relevant to fossil fuel extraction, especially from unconventional fossil fuel resources, and in CCS research. The science underlying fossil fuel conversion and use is at a more mature stage and is less of a priority for research council support.

35. The research councils should prioritise three broad categories of research across the fossil fuel/CCS domain: energy-related activities in the sub-surface; carbon capture, storage and utilisation; and cross-cutting challenges relating to the geosciences, socio-economic aspects and environmental impacts.

Electrochemical energy technologies and storage

36. A strategic framework, linking different electrochemical energy technologies in terms of research needs, skills and shared infrastructure, should be created. This framework should be utilised when planning research programmes in order to identify potential synergies in research capabilities and to maximise collaborative efforts.

37. The research councils should continue to fund basic 'blue skies' research into electrochemical energy phenomena, for example through the EPSRC *materials for energy* research area, as well as more applied research.

Wind, wave and tide

38. Research is needed on a range of technical issues relating to wind, wave and tidal energy. A key challenge is to understand how technologies operating at different scales (component – device – array – ecosystem) link together. Given the applied nature of many of the research challenges, close linkages with other innovation bodies such as the Technology Strategy Board (TSB) and the Energy Technologies Institute (ETI) are essential.

39. Further consideration should be given to the social, economic, environmental and planning/policy issues that relate to wind, wave and tidal energy.

Bioenergy

40. The research councils, especially BBSRC and EPSRC, should seek to integrate better their research investments and should consider joint funding of programmes and projects. Greater clarity about the orientation of research council energy strategies in terms of the balance between basic and applied research would be helpful to both the research community and users.

41. The research councils should continue to support a broad portfolio of research in the bioenergy field and should make efforts to ensure that research is linked to field trials and monitoring activities. Longer-term research support, perhaps ten years, with a five year breakpoint might be appropriate for research linked to field trials.

Energy infrastructure

42. The research councils should work with Ofgem and other late-stage innovation funders to ensure that Research Council-funded programmes complement and provide basic underpinning research for demonstration and deployment projects. The roles and responsibilities of the research councils and other innovation bodies along the innovation chain should be clarified.

43. The research councils should ensure that a range of research challenges, spanning systems planning and operation, policy and market design and component technologies, are met.

Acronyms

AHRC	Arts and Humanities Research Council
BBSRC	Biotechnology and Biological Sciences Research Council
BIS	Department of Business, Innovation and Skills
BSBEC	BBSRC Sustainable Bioenergy Centre
CCC	Committee on Climate Change
CCS	Carbon capture and storage
CERT	Committee on Energy Research and Technology (IEA)
CLG	Department of Communities and Local Government
CSA	Chief Scientific Adviser
CSR	Comprehensive Spending Review
DECC	Department of Energy and Climate Change
Defra	Department of Environment, Food and Rural Affairs
DfT	Department for Transport
EERA	European Energy Research Alliance
EII	European Industrial Initiative (SET Plan)
EPSRC	Engineering and Physical Sciences Research Council
ESRC	Economic and Social Research Council
ETI	Energy Technologies Institute
EU	European Union
FCO	Foreign and Commonwealth Office
FP	Framework Programme (EU)
GHG	Greenhouse gas
HEI	Higher Education Institution
HVDC	High voltage direct current
IA	Implementing Agreement (IEA)
IEA	International Energy Agency
IP	Intellectual property
JP	Joint Programme (EERA)
KTN	Knowledge Transfer Network
LCNF	Low Carbon Networks Fund
MoU	Memorandum of Understanding
NAO	National Audit Office
NERC	Natural Environment Research Council
NUCLEAR	Nuclear Universities Consortium for Learning, Engagement and Research
Ofgem	Office of Gas and Electricity Markets
OECD	Organisation for Economic Cooperation and Development
OLEV	Office of Low Emission Vehicles
RAMO	Reliability, availability, maintainability and operability
RCEP	Research Councils UK Energy Programme
RCUK	Research Councils UK
R&D	Research and development
RD&D	Research, development and demonstration
RED	Renewable Energy Directive (EU)
REF	Research Excellence Framework
RIIO	Revenue = incentives + innovation + outputs (Ofgem)
SET Plan	Strategic Energy Technology Plan (EU)
SIN	Science and Innovation Network (FCO/BIS)
STFC	Science and Technology Facilities Council
SUPERGEN	Sustainable Power Generation (EPSRC research consortia)
TRL	Technology Readiness Level
TSB	Technology Strategy Board
UKCCSRC	UK CCS Research Centre
WRAP	Waste and Resources Action Programme

1. Introduction

The 2010 International Review of the Research Councils UK Energy Programme Panel noted the quality of UK energy research but recommended that a fully integrated roadmap for research targets be completed. This report, developed through an independent consultative process, responds to that recommendation.

This *Energy and Research Training Prospectus* is a contribution to the evidence base on which the research councils can plan their forward activities in the energy field. The Prospectus has been developed independently through an Engineering and Physical Sciences Research Council (EPSRC) Senior Fellowship, the Energy Strategy Fellowship.

The production of the Prospectus follows an International Review of the Research Councils UK (RCUK) Energy Programme conducted in 2010.[2] The International Panel found that in almost all of the areas they reviewed they found "interesting, leading edge and world class research" and that "the excellent international reputation of UK research is deservedly earned"

However, the Panel identified weaknesses arising from "a lack of a sustained long-term coherent energy research programme across the different funding bodies, competition between the funding bodies, a lack of transparency particularly as perceived by the researchers and poorly executed or non-existent mechanisms for moving technologies from the research stages to early demonstration, application and deployment". The Panel also had concerns about the availability of long-term career paths for doctoral students and post-doctoral research associates.

The Panel therefore recommended the establishment of "a fully integrated 'roadmap' for UK research targets be completed and maintained to allow all to know and understand what is considered essential to meet society's needs". The Energy Strategy Fellowship[3] was established in 2012 through open competition in response to this recommendation. The Fellowship team comprises a team of four people based at Imperial College London[4]. RCUK asked the Fellowship team to engage "a broad array of stakeholders including academia, industry, environmental activists, research funders, policymakers and others, from both the UK and beyond" and to act independently in doing so. The process through which the prospectus has been developed reflects this stakeholder-driven, consultative approach (Box 1).

Following the recommendations of the International Review Panel, the development of the Prospectus has taken into account the contribution that Research Council-supported energy research might make to the achievement of the UK's policy goals, not only ambitious climate change objectives but also the other elements of energy policy – security and affordability – and potential contributions to economic growth and competitiveness.

The report is organised as follows. Section 2 describes ways of mapping the energy research and development (R&D) domain and the innovation process. Section 3 outlines responsibilities for funding public sector energy R&D in the UK, noting in particular the collective and individual roles of the research councils. To frame R&D needs, Section 4 addresses the range of possible energy futures, globally and in the UK, against which it would be prudent to plan energy R&D activities. Section 5 considers how well the UK is currently placed to address future energy challenges in terms of investment in energy research development and demonstration (RD&D), industrial capabilities and scientific competences. Sections 6 and 7 present high level findings and recommendations based on the workshops and consultations. Section 6 focuses on specific areas of energy research whilst Section 7 covers cross-cutting issues such as the way research is supported and conducted, and connections between and beyond the research councils. Section 8 draws together high-level conclusions.

BOX 1: How the Prospectus was developed

During a *scoping phase*, a comprehensive review of relevant energy roadmaps, pathways and scenario exercises was conducted. Extensive consultation with stakeholders across the energy landscape encouraged buy-in and clarified the relationship between the RCUK Prospectus and other roadmaps and needs assessments related more to deployment. Consultees urged the Fellowship team to organise workshops around clusters of related energy topics, taking account of underlying research skills.

The *evidence-gathering phase* relied heavily on workshops bringing the research community and stakeholders together. 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. A set of six residential workshops provided the space for experts to consider technical issues in depth. These covered *Fossil Fuels and CCS, Energy in the Home and Workplace, Energy Infrastructure, Bioenergy, Transport Energy* and *Electrochemical Energy Technologies and Energy Storage.* 'Light-touch' activities were conducted in respect of: *Industrial Energy; Wind, Wave and Tide*; and *Nuclear Fission.* 246 individuals participated in the workshops, the majority from academia as well as others from industry, the public sector and NGOs.

At the *synthesis stage*, the workshops reports were 'mined' and combined with contextual information to produce the peer-reviewed Prospectus Reports. This report constitutes a top-level document that synthesises the topic-specific Prospectus Reports, which are available online. A cross-sectoral Advisory Group (Annex D) provided guidance on the development of the Prospectus and reviewed the findings.

[2] *Progressing UK Energy Research for a Coherent Structure with Impact: Report of the International Panel for the RCUK Review of Energy 2010, http://www.rcuk.ac.uk/documents/reviews/reviewpanelreport.pdf*

[3] *http://www3.imperial.ac.uk/rcukenergystrategy*

[4] *http://www3.imperial.ac.uk/rcukenergystrategy/people*

2. Mapping energy R&D

The energy innovation landscape is complex. Diverse energy applications are connected by the same underlying research skills. Feedback from the demonstration and deployment of energy technologies can stimulate many research challenges.

2.1 Energy applications and underpinning science

The energy research and innovation landscape is complex. Underpinning scientific disciplines can contribute to a range of energy applications. For example, the geological sciences are relevant to radioactive waste disposal (nuclear), coal, oil and gas extraction (fossil fuels), carbon storage (fossil fuels) and geothermal energy (renewables). In developing the Prospectus, we have followed the EU/International Energy Agency (IEA) energy R&D nomenclature[5] (Table 1) to provide structure to our activities and as a check for completeness of coverage. Individual research councils, the RCUK Energy Programme and other bodies in the energy innovation landscape categorise their activities in different ways.

The IEA nomenclature builds on an engineering/physical sciences framing of energy challenges. Whilst useful for conceptualising the variety of the energy research landscape it has a number of weaknesses. These include:

- a limited emphasis on energy demand;
- the contributions of the environmental and social sciences and economics are summarised only briefly under a 'cross-cutting' energy research area; and
- the contribution of the biological sciences is summarised in a single topic, energy crops, and implicitly in biomass/biofuels processing.

The nomenclature is the basis for collecting and reporting international energy R&D statistics.[6] However, the variety of

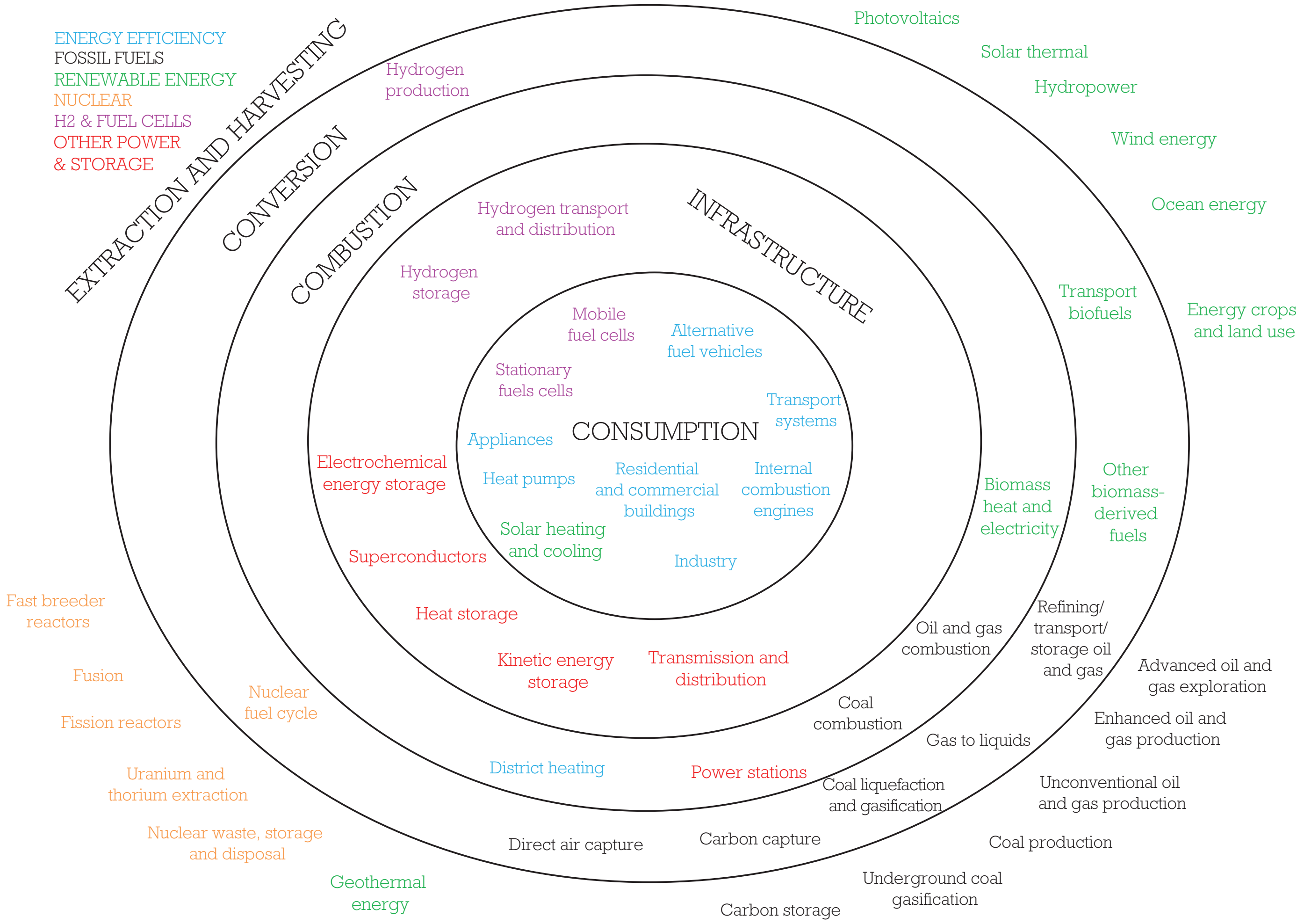
Table 1: IEA/EU Energy R&D Nomenclature

Area	Sector
Energy Efficiency	Industry Buildings, appliances and equipment Transport Other energy efficiency
Fossil Fuels	Oil and gas Coal CO_2 capture and storage
Renewable Energy Sources	Solar energy Wind energy Ocean energy Biofuels (incl. liquids, solids and biogases) Geothermal energy Hydroelectricity Other renewable energy sources
Nuclear	Nuclear fission Nuclear fusion
Hydrogen and Fuel Cells	Hydrogen Fuel cells
Other Power and Storage Technologies	Electric power conversion Electricity transmission and distribution Energy storage
Other Cross-cutting Technologies/Research	Energy system analysis Other

[5] *International Energy Agency, IEA Guide to Reporting Energy RD&D Budget/Expenditure Statistics, June 2011 edition, http://www.iea.org/stats/RDD%20Manual.pdf*

[6] *International Energy Agency (2013): Energy Technology Research and Development Database (Edition: 2013). Mimas, University of Manchester. DOI: http://dx.doi.org/10.5257/iea/et/2013*

Figure 1: The Energy R&D 'Wheel'



methods used for categorising energy R&D by research and innovation bodies in the UK makes it difficult to compare and report activity internationally expect at the most aggregated level, as noted by the IEA.[7]

Recommendation: In reporting energy R&D activity for statistical purposes, UK energy research and innovation bodies should adopt, as far as possible, the EU/IEA energy R&D nomenclature to facilitate comparison both internationally and across organisations within the UK.

However, in framing new and innovative research activities, especially those of an interdisciplinary nature, the research councils and other bodies should not be constrained by the EU/IEA nomenclature. It provides a good basis for mapping applied energy research underpinned by engineering and the physical sciences, but is less appropriate in other scientific domains relevant to energy. Figure 1 shows the *Energy R&D Wheel* developed by the Fellowship team building on the IEA nomenclature. This takes 49 detailed energy research sub-topics and places them in a series of concentric rings. The outer ring refers to the extraction or harvesting of primary energy. The centre refers to energy consumption and intermediate rings to energy conversion/combustion and the infrastructure that links supply and demand. Individual topics have been colour-coded according to the first six IEA energy research areas. Energy applications that are underpinned by related scientific and technical knowledge have been placed, as far as possible, adjacent to each other. The placing of the topics draws out the interconnectedness of the energy research and innovation landscape. It also underlines the fact there are many ways of dividing the energy research landscape, none of them more 'correct' than any other. The diagram has facilitated the identification of related energy research applications and those based on the same underlying science.

Like the nomenclature, the *Energy R&D Wheel* has limitations. Cross-cutting environmental, social and economic research is not explicitly represented. Furthermore, micro-generation has been located at the centre of the diagram in the 'consumer' zone although it could also be regarded as energy harvesting or conversion.

[7] *International Energy Agency, Energy Technology RD&D Budgets Documentation for Beyond 2020 Files, p.12. Energy Technology Research and Development Database (Edition: 2013). Mimas, University of Manchester. DOI: http://dx.doi.org/10.5257/iea/et/2013*

2.2 The innovation process

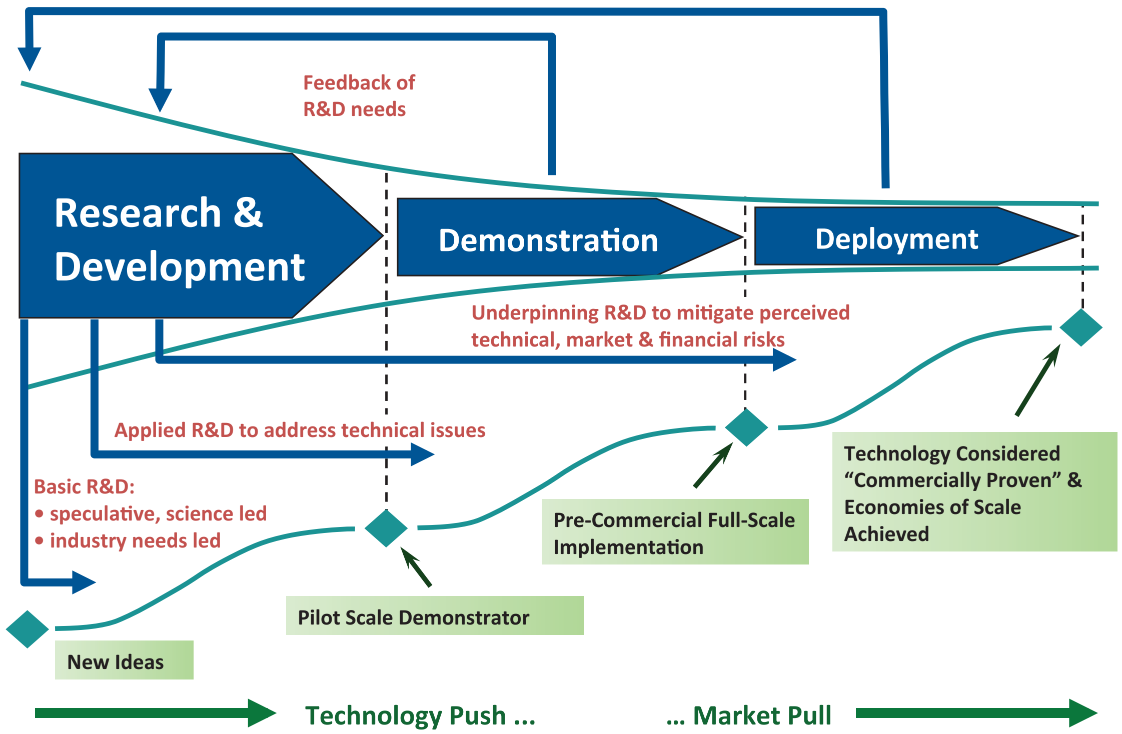
Technological innovation covers all stages of development from basic and applied research through to commercial demonstration and deployment (Figure 2). The research councils focus on the earlier stages of the innovation process. Technological innovation is supported by institutions, policies and regulations. Non-technological innovation in these areas can be important and is not readily captured in diagrams such as Figure 2.

The OECD Frascati Manual on research and experimental development,[8] which provides the framework for UK and EU funding definitions, separates basic research, applied research and 'experimental development'. The latter covers development, pilot plant and certain demonstration activities, which are largely outside the scope of the research councils. Use of the Technology Readiness Level (TRL) concept to characterise stages in the innovation chain has become ubiquitous within the UK energy innovation community (Box 2). TRLs 1-2 correspond roughly to basic research, TRLs 3-5 to applied research and development, TRLs 6-7 to demonstration and TRLs 8-9 to pre-commercial deployment. In this report, the Frascati R&D definitions are used.

Recommendation: The TRL framework, when it is used, should be applied with greater rigour than at present.

Figure 2 makes it clear that innovation does not necessarily proceed in a linear fashion from basic research through to deployment. While some basic research challenges are of a 'blue skies' nature, others may be defined by problems identified at later stages in the innovation process, for example in pilot plants, demonstration or deployment. It is useful to distinguish between 'science-inspired' and 'application-inspired' research challenges, both of which feature in the energy domain.

Figure 2: The energy innovation process



Source: Energy Research Partnership, 2007[9]

BOX 2: Technology Readiness Levels

The Technology Readiness Level (TRL) concept was originally developed by NASA in the 1980s. The purpose is to characterise the technological maturity of components and sub-systems, which form part of a larger technical system. The use of the concept within the UK energy innovation community has become both ubiquitous and somewhat casual. TRLs are seldom mentioned in groups of less than two or three, blurring the distinctions between the nine original TRL levels. The concept is often applied to entire technologies, e.g. wind. A more rigorous approach would be to apply the TRL concept to subsystems or aspects of wind technology development e.g. array design, foundations, braking systems, environmental assessment etc. Different subsystems may be at different TRL levels.

[8] *OECD, Frascati Manual: Proposed Standard Practice for Surveys on Research and Experimental Development, 2002. http://dx.doi.org/10.1787/9789264199040-en*
[9] *Energy Research Partnership, UK Energy Innovation, 2007. http://www.energyresearchpartnership.org.uk/tiki-download_file.php?fileId=16*

3. Energy R&D funding landscape

The research councils play a unique role in stimulating early stage energy research. The research challenges being addressed by the Research Councils Energy Programme can be framed in different ways. All of the participating research councils have an important role to play.

3.1 The overall picture

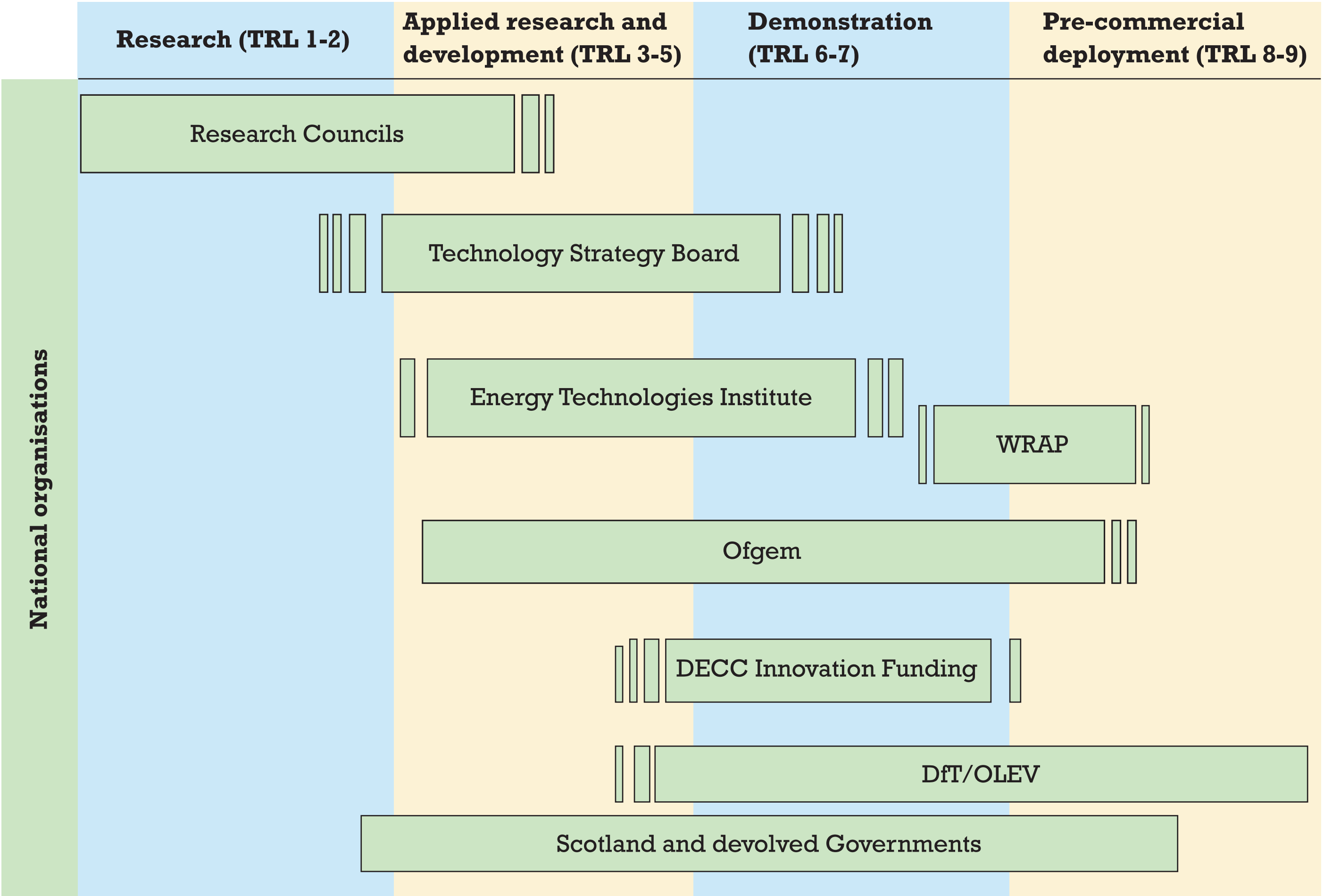
While the research councils are the primary audience for this report, they form only part of the wider energy innovation system in the UK. Other public sector bodies, both government departments and arms-length bodies, support research of a more applied character as well as development and demonstration activities. Figure 3 provides a schematic of the current technology funding landscape, classifying organisations according to the parts of the innovation chain on which they are primarily focused. A variety of bodies with different remits operate at the applied R&D/demonstration stages, whereas the research councils are almost uniquely responsible for early stage basic and applied research.

The desirability or otherwise of having a multiplicity of bodies supporting energy innovation is beyond the scope of this report. However, it is worthwhile noting that different bodies ostensibly working within the same parts of the innovation chain have different objectives. For example, the Technology Strategy Board (TSB) focuses on economic opportunities while DECC focuses on meeting energy and climate change targets and the reduction of energy costs. In 2012, DECC published its first Science and Innovation Strategy.[10] The Low Carbon Innovation Coordination Group (LCICG) has been established to ensure that activities are coherent across the energy innovation funding landscape.

The effectiveness of coordination of the UK energy innovation system has improved[11] since the publication of critical National Audit Office (NAO) report concerning renewable energy support in 2010. The systematic development of technology innovation needs assessments (TINAs) for a range of technologies (see Section 5.2) and work on common metrics for different innovation bodies are seen as positive steps.

In some parts of the energy domain, a considerable amount of R&D is undertaken by the private sector, which also funds research in universities (see Section 5.1). The volume of energy R&D conducted by the private sector exceeds that supported by the public sector in some areas, notably fossil fuels, transport energy and energy-consuming devices and equipment.

Figure 3: The UK Energy Technology Funding Landscape



Source: DECC, 2013

[10] *Department of Energy and Climate Change, Science and Innovation Strategy 2012. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48335/5107-decc-science-innovation-strategy-2012.pdf*

[11] *National Audit Office, Public funding for innovation in low carbon technologies in the UK: Briefing for the House of Commons Energy and Climate Change Select Committee, October 2013. http://www.nao.org.uk/wp-content/uploads/2013/10/Briefing-for-ECC-Public-funding-for-innovation-in-low-carbon-technology.pdf*

The volume of energy R&D conducted by the private sector exceeds that supported by the public sector in some areas, notably fossil fuels, transport energy and energy-consuming devices and equipment.

3.2 The role of the research councils

Five research councils have an interest in energy research and participate in the RCUK Energy Programme (RCEP): the Biotechnology and Biological Sciences Research Council (BBSRC); EPSRC; the Economic and Social Research Council (ESRC); the Natural Environment Research Council (NERC); and the Science and Technology Facilities Council (STFC). The research councils have three common objectives as specified in their Royal Charters:

- to promote and support high-quality basic, strategic and applied research and related post-graduate training in their respective scientific domains;
- to advance knowledge and technology, and provide trained scientists and engineers, which meet the needs of users and beneficiaries and contribute to the economic competitiveness of the UK and the quality of life; and
- to provide advice, disseminate knowledge, and promote public understanding.

The specific objectives of individual research councils vary (see Annex A for a fuller comparison of the Royal Charters, the areas of science that each research councils should promote, and main users and beneficiaries). Key differences include:

- STFC must develop and provide facilities and technical expertise in support of basic, strategic and applied research.
- NERC should support surveys and long-term environmental observation and monitoring.
- ESRC and NERC should contribute to the effectiveness of public services and policy.
- EPSRC and NERC should promote and support the exploitation of research outcomes.
- NERC, EPSRC and STFC should generate public awareness and encourage public engagement (an implied two-way process) rather than simply promote public understanding.

Broadly, the research councils operate under the Haldane principle under which priorities are established by the scientific community rather than through the political process. However, there has been an increasing emphasis on social, economic and commercial impact over the last 20 years, reflected in the identification of the needs of 'user and beneficiaries' in the 1993 revisions to the Royal Charters.

RCUK is a partnership between the research councils that aims to optimise the ways that the research councils work together to deliver their goals and enhance the overall performance and impact of UK research, training and knowledge transfer. RCUK does not supersede the accountabilities of individual research councils.

RCUK acts as the umbrella for a cross-council Energy Programme, while individual research councils conduct energy-relevant activities within the framework of their Strategic Plans. Each of the research councils is working to a Delivery Plan that corresponds to the current Comprehensive Spending Review (CSR) period 2011-15. Table 2 summarises how each of the research councils approaches energy within its Delivery Plan. EPSRC, which leads the RCUK Energy Programme, has the most explicit energy focus. Other research councils have energy

Table 2: The Research Councils' Current Approaches to Energy

	Strategic/Delivery Plans	Location of energy
BBSRC	Maximising Economic Growth in The Age of Bioscience[12]	Grand Challenge: *Industrial biotechnology and bioenergy*
EPSRC	The Heart of Discovery and Innovation[13]	Energy is one of four main themes; leads RCUK Energy Programme
ESRC	Delivering Impact through Social Science[14]	*Environment, Energy and Resilience* is one of seven social science areas
NERC	The Business of the Environment[15]	*Benefiting from Natural Resources* Challenge
STFC	Impact through Inspiration and Innovation[16]	Within *Solutions for Global Challenges* theme
RCUK[17]	• Support excellent research that has an impact on the growth, prosperity and wellbeing of the UK. • Offer a diverse range of funding opportunities, foster international collaborations and provide access to the best facilities and infrastructure around the world. • Support the training and career development of researchers and work with them to inspire young people and engage the wider public with research. • Work in partnership to maximise the impact of research on economic growth and societal wellbeing.	RCUK Energy Programme

Source: Research Council Strategic and Delivery Plans; RCUK website

[12] *http://www.bbsrc.ac.uk/strategy*
[13] *http://www.epsrc.ac.uk/SiteCollectionDocuments/Publications/corporate/EPSRC_strategic_plan_2010.pdf*
[14] *http://www.esrc.ac.uk/Image/Strategic_Plan_FINAL_tcm11-13164.pdf*
[15] *http://www.nerc.ac.uk/publications/strategicplan/documents/the-business-of-the-environment.pdf*
[16] *http://www.stfc.ac.uk/resources/pdf/vision.pdf*
[17] *http://www.rcuk.ac.uk/Pages/Home.aspx*

Table 3: The Focus of Research Council Energy Research Activity

RCUK Energy Programme	EPSRC Energy Theme
Conventional generation	Carbon capture and storage Conventional generation and combustion
Energy efficiency[2]	Energy efficiency (end use energy demand) Transportation operations and management
Nuclear power[1,3]	Nuclear fission
Power networks	Energy networks
Renewable energy[1,4]	Bioenergy Marine wave and tidal Solar technology Wind power
Socio-economic and policy[2]	Whole energy systems
Sustainable energy vectors[3]	Fuel cell technology Hydrogen and alternative energy vectors
Underpinning energy sectors[3]	Energy storage Materials for energy applications
Fusion[3]	Materials engineering - metals and alloys Nuclear fission Performance and inspection of mechanical structures and systems Plasma and lasers UK Magnetic Fusion Research Programme

Source: EPSRC

***Notes:** 1) area with a significant NERC interest; 2) area with a significant ESRC interest; 3) area with a significant STFC interest (in terms of provision of facilities/expertise); 4) area with a significant BBSRC interest.*

interests but these are less visible and energy is generally embedded in wider themes or challenges.

Within the RCUK Energy Programme, subsets of the research councils sometimes pool resources for key interdisciplinary investments (e.g. the UK Energy Research Centre (UKERC) and the End Use Energy Demand (EUED) Centres), but often individual research councils make independent investments reflecting their own area of interest which contribute to the Programme as a whole.

Table 3 compares the RCUK Energy programme portfolio with research areas covered by EPSRC's energy theme. BBSRC's activities are closely aligned with EPSRC's bioenergy research area, but ESRC's, NERC's and STFC's activities are more cross-cutting in nature. The alignment between the RCUK Energy Programme and EPSRC is good, as might be expected given that EPSRC has most explicitly identified energy as a priority topic and it leads the Energy Programme. However, the terms used to classify the RCUK Energy Programme do not always provide a clear guide to the nature of the work that might be supported by individual research councils. For example, any NERC work related to 'unconventional' oil and gas extraction is, ironically, most closely aligned with the 'conventional' generation topic, which covers fossil fuels. The title 'sustainable energy vectors' provides little clue to the fact that it covers fuel cells and hydrogen more specifically.

Recommendation. The research councils should adopt a more rigorous and precise approach to defining areas of energy research and, if possible, avoid terms subject to misinterpretation such as 'conventional' or 'sustainable' unless their meaning is well understood across the relevant research communities.

Recommendation. The communication of the cross-council RCUK Energy Programme should better reflect the potential contribution of all research councils. The Programme is often confused with the EPSRC energy theme. Other research councils could help by clearly identifying the contributions that their Strategic and Delivery Plans make to energy research.

The communication of the cross-council RCUK Energy Programme should better reflect the potential contribution of all research councils.

3.3 International engagement

The UK is connected to the wider international energy innovation system through:

- participation in the specification and execution of the EU Framework R&D Programmes (Horizon 2020 from 2014);
- participation in IEA Technology Implementing Agreements (IAs);
- bilateral technology co-operation framed by formal Memoranda of Understanding (MoUs);
- informal bilateral co-operation; and
- the activities of multinational companies, either through overseas R&D investments by UK-domiciled companies or overseas companies' investments in the UK.

The UK has provided input to the current Framework Programme (FP7) via the Energy Committee which comprises representatives of Member States. EU energy technology activities are co-ordinated through the European Strategic Energy Technology Plan (SET Plan), which is designed to accelerate the development and deployment of cost-effective low carbon technologies through planning, implementation, resources and international cooperation. The UK, via DECC, is represented on the SET Steering Group.[18] The European Energy Research Alliance (EERA) has been established to accelerate the development of new energy technologies by conceiving and implementing Joint Programmes (JPs) in support of the SET Plan. UKERC acts as the focal point for UK participation in EERA. EERA activities complement the European Industrial Initiatives (EIIs) also associated with the SET Plan.

IEA Implementing Agreements are multilateral energy technology cooperation initiatives bringing together governments, industry and academia. The UK is reported to participate in 25 of the IEA's 42 IAs, more than any other country except the US, Canada and Japan.[19] UK participation is coordinated by DECC which is represented on IEA's Committee for Energy Research and Technology (CERT).

EPSRC has concluded MoUs with a number of priority countries including China, India and the US.

[18] *European Commission, The European Strategic Energy Technology (SET) Plan: Towards a low-carbon future, http://ec.europa.eu/energy/technology/set_plan/set_plan_en.htm*
[19] *International Energy Agency, Energy Technology Initiatives: Implementation through Multilateral Co-operation, http://www.iea.org/publications/freepublications/publication/technology_initiatives-1.pdf*

4. What energy futures should we anticipate?

There are great uncertainties about the future development of energy systems. But energy efficiency and new energy technologies such as renewables play some role in almost all energy scenarios. This justifies RCUK's portfolio approach to energy research. 'Whole-systems' interdisciplinary research can provide a link to wider policy developments.

4.1 Introduction

Potential changes in the energy system at the UK and global levels are relevant to the setting of energy R&D research and training priorities. This section reviews a small number of mainstream global and UK energy scenarios that span a range in terms of aspirations and expectations about the future. It is reasonable to expect that research portfolios should be robust against the range of possible futures that these represent.

The biggest differentiator between published scenarios is whether or not the world meets the UN Framework Convention on Climate Change (UNFCCC) target of keeping global temperature increases to within 2˚C above pre-industrial levels. The UK's 80% greenhouse gas emissions reduction target by 2050 is seen as an equitable contribution to this goal. This section considers two types of scenarios: normative scenarios that incorporate technology and market changes compatible with hitting the 2˚ target; and exploratory or business-as-usual scenarios that envisage a much bigger role for incumbent technologies. Scenarios from both the public and private sectors are considered.

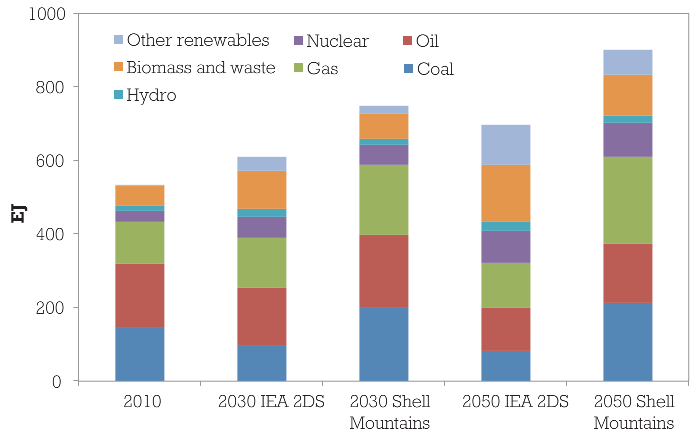
4.2 Global energy scenarios

Two global scenarios are considered, a normative scenario from the *International Energy Agency* and an exploratory one from *Royal Dutch Shell*. The IEA's 2 Degrees (2DS) scenario[20] describes how the global energy system would need to evolve, and the technologies and policies that would need to be in place, if there were to be an 80% chance of hitting the 2˚C target. The Shell *New Lens* Scenarios,[21] based on a mixture of geopolitical forecasting and analytical modelling, are intended to provide challenging visions of the future. The *Mountains* scenario was chosen for comparison rather than its companion, the *Oceans* scenario, because it contrasts more strongly with the 2DS scenario in terms of technology deployment. The Shell scenarios imply that global temperatures will increase far in excess of 2˚C.

Figure 4 compares primary energy demand in two scenarios for 2030 and 2050. Global energy demand in the *Mountains* scenario is 29% higher than in the 2DS scenario by 2050, with fossil fuels making a far greater contribution to the energy mix. The use of natural gas and coal is much higher in *Mountains* in 2050 than it is today. The use of coal and oil in 2050 is lower than today in the 2DS scenario while the use of natural gas is broadly similar. The 2DS scenario includes significantly improved energy efficiency, coupled with a major shift to biomass and other renewable energy sources. Unconventional fossil fuel sources, chiefly shale gas, expand in the *Mountains* scenario.

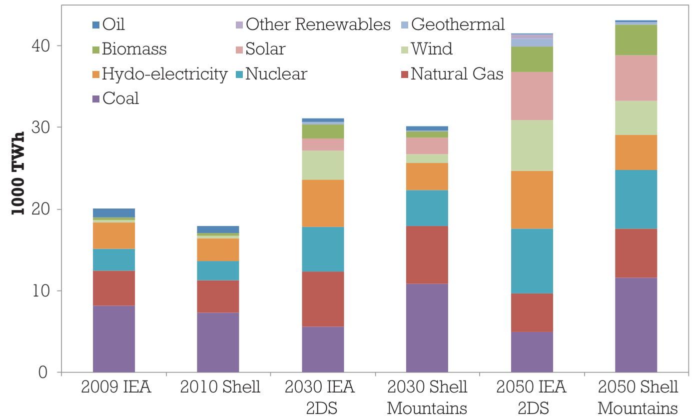
Figure 5 compares the global electricity generation mix in the two scenarios for 2030 and 2050 with today's mix.[22] Both scenarios envisage similar and substantial increasing electricity demand. The global electricity system is largely decarbonised by 2050 in the 2DS scenario, with low-carbon nuclear, hydro, solar and wind accounting for the majority of electricity supplies.

Figure 4: Global primary energy supply



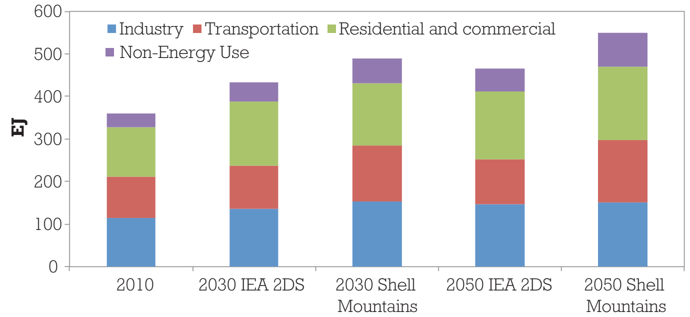
Source: IEA and Shell

Figure 5: Global electricity generation mix



Source: IEA and Shell

Figure 6: Global final energy demand including non-energy uses



Source: IEA and Shell

[20] *IEA, 'Energy Technology Perspectives 2012', http://www.iea.org/etp/*
[21] *Shell New Lens Scenarios, http://www.shell.com/global/future-energy/scenarios/new-lens-scenarios.html*
[22] *There are methodological differences between the way Shell and IEA treat electricity. Baseline figures (2009/2010) are therefore presented for both scenarios.*

Most of the remaining coal capacity, and some gas plant, has CCS fitted so that even fossil-fuel generation is relatively low-carbon. 'Other' renewable technologies such as geothermal and marine renewables play only a small role. The overall picture is that of a diversified electricity system with substantial roles being played by low-carbon generation technologies. Fossil fuels account for almost half of electricity generation by 2050 in the *Mountains* scenario, with coal taking the largest market share. A significant amount of CCS is deployed and 30% of CO_2 emissions are captured by 2050. There is still a significant deployment of low-carbon technologies in this scenario, but at lower levels than in 2DS.

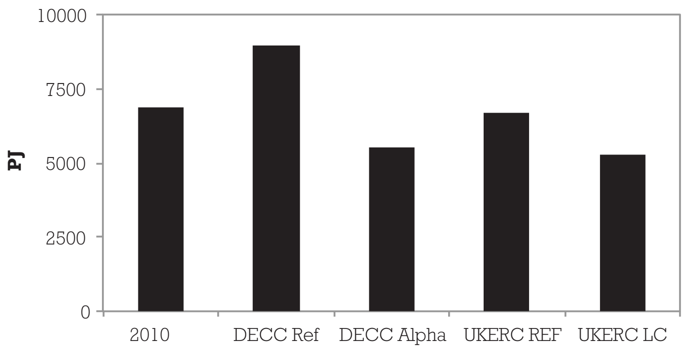
Figure 6 compares final energy demand by sector in the 2DS and *Mountains* scenarios. Both scenarios envisage energy demand rising, but growth is much slower in 2DS. The main difference lies in transport. The 2DS scenario foresees transport energy demand increasing by 12% by 2050. In developing countries, transport energy demand rises by 66% due to economic development and population growth. However, demand falls by 30% in developed countries due to more efficient fuel use and increased use of electric and hybrid vehicles. Globally, transport demand is met by a combination of oil (~60%), biomass (25%) electricity (10%) and a small quantity of hydrogen. The *Mountains* scenario sees transport demand rising by 53% by 2050, with a significant growth in compressed natural-gas, and electric/hydrogen vehicles which account for 20% and 40% respectively of passenger road transport.

4.3 UK energy scenarios

Two scenario sets were consulted to gain a picture of the UK's possible range of energy futures. The first was the revised UKERC Energy 2050 scenario set,[23] which used the UK MARKAL model,[24] a bottom-up, technology-rich cost optimisation model. The two scenarios reviewed from this set were the reference scenario (REF), which assumes that current policies extend into the future and a low-carbon scenario (LC), which is compatible with the 2050 GHG target. Current policies in REF include the assumption that the carbon price floor will rise to £30/tonne of CO_2 by 2020 and £70/tonne by 2030 in line with current government intentions. This provides a significant incentive for low carbon technologies even in the absence of other measures.

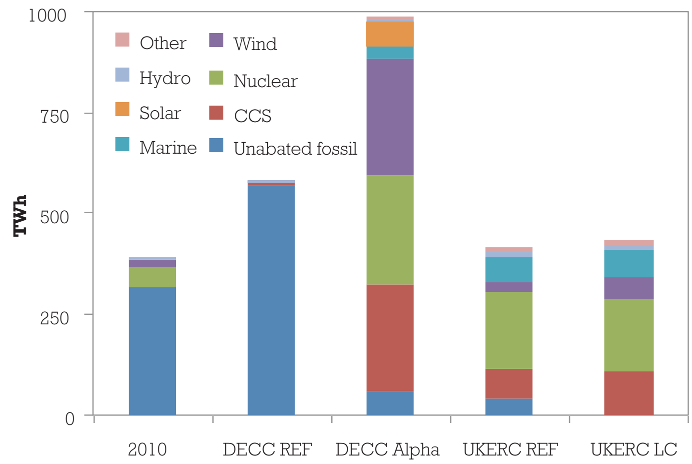
The second scenario set was derived using the DECC 2050 *Pathways Calculator*[25] which integrates user-specified assumptions about the level of effort expended on different energy technologies. Two pathways, the *Reference Case* pathway and *Pathway Alpha*, were selected from a set published by DECC.[26] The former assumes minimal efforts to decarbonise or diversify energy supply, whilst the latter assumes a balanced effort to decarbonise across all sectors resulting in compliance with the 80% GHG reduction target.

Figure 7: Primary UK energy demand in 2050 under different scenarios



Source: DECC and UKERC

Figure 8: Electricity generation by type in 2050



Source: DECC and UKERC

Primary annual energy demand falls by around 20% by 2050 in both the DECC *Alpha* and UKERC *LC* scenarios (Figure 7). In the DECC *Reference Case*, where very little action is taken, primary demand grows by 35% by 2050. The UKERC REF scenario foresees primary energy demand being similar to the current level in 2050. The key message from Figure 7 is that energy efficiency needs to play a significant role in meeting climate policy objectives.

The differences between the DECC pathways and the UKERC scenarios are even more pronounced in relation to electricity generation (Figure 8). Total generation increases by 51% 2010-50 in the DECC *Reference Case* and by 155% in DECC *Alpha*. In contrast, generation rises by 7% in UKERC *REF* and by 12% in UKERC *LC*. Generation is higher than the reference cases in the *Alpha* pathway and *LC* scenario because there is greater electrification of energy demand for transport and heating in the carbonisation scenarios.

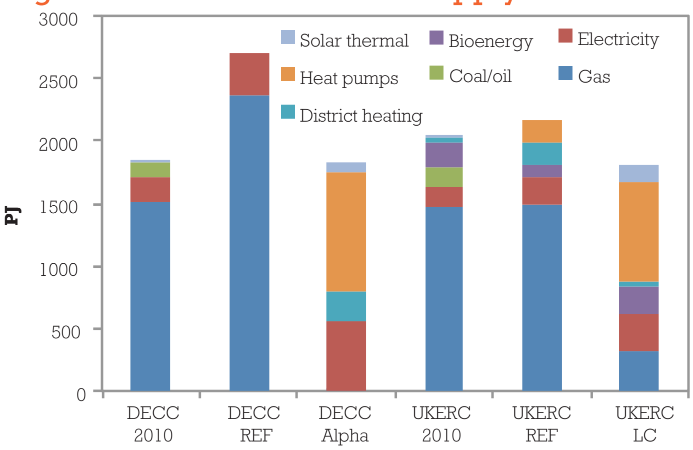
[23] *UKERC, 'Energy 2050 Scenarios: Update 2013', http://www.ukerc.ac.uk/support/ES_RP_UpdateUKEnergy2050Scenarios*
[24] *UCL Energy Institute, 'UK MARKAL model', http://www.ucl.ac.uk/silva/energy-models/models/uk-markal*
[25] *DECC, '2050 Pathways Calculator,' https://www.gov.uk/2050-pathways-analysis*
[26] *DECC, '2050 Pathways Analysis Report', 2010, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/68816/216-2050-pathways-analysis-report.pdf*

The generation mix is very different across the scenarios. In the DECC *Reference Case,* unabated gas-fired generation continues to dominate and indeed drives out low-carbon generation technologies. In all other scenarios, including the UKERC *REF* scenario, unabated fossil fuels are either largely or wholly driven from the system. The contributions of plant fitted with CCS, nuclear and wind are similar in the *Alpha* case. Nuclear has a larger share of a smaller market in the UKERC scenarios while CCS and wind have smaller shares. The two UKERC scenarios are remarkably similar. This is because of the carbon price floor assumption in the *REF* scenario which incentivises low-carbon technologies. The DECC *Alpha* and both UKERC scenarios foresee significant roles for other renewable technologies, solar in the case of DECC *Alpha* and marine renewables (wave and tide) in the UKERC scenarios.

The overarching message from Figure 8 is that the range of possible futures for the UK electricity sector is very broad in terms of both the size of the market and the generation mix. No single technology can be ruled out, even solar which is not well suited to UK's climatic conditions or marine renewables which are at a less mature stage of development.

How demand for heat and transport fuels is met is critical in understanding different views of UK energy futures. Figure 9 shows considerable uncertainty over the mix of technologies used to supply heat to residential and commercial sectors by 2050, though there is more convergence over the absolute level of heat demand. Only the DECC *Reference Case* foresees a significant increase in UK heat demand, almost 50% by 2050. Both the reference scenarios envisage gas meeting the majority of heat demand, though there is some penetration of district heating and heat pumps in the UKERC *REF* scenario. The DECC *Alpha* pathway and the UKERC *LC* scenario are remarkably similar in terms of the significant role assigned to electric heat pumps. However, they differ as to how residual heat demand might be met. DECC *Alpha* assumes mostly electricity with some district heating. UKERC *LC* has a more balanced mix for gas, electricity and bioenergy.

Figure 9: Sources of UK heat supply in 2050



Note: *Due to methodological differences, separate baseline figures are shown for both sets of scenarios*

In the transport sector the two *Reference* scenarios contain no substantive move away from conventional internal-combustion engines for road transport. In DECC's *Alpha* pathway, electric and plug-in hybrid vehicles account for 60% of mileage by 2050, with over half the UK vehicle fleet consisting of plug-in hybrids and a further 10% consisting of battery electric vehicles. Almost all buses are plug-in hybrids in this scenario. UKERC's *LC* scenario envisages battery-electric vehicles playing no significant role in the UK vehicle fleet by 2050 due to high infrastructure costs and up-front capital requirements. This scenario foresees conventional hybrids playing a big mid-term role, followed by a move to bioethanol in the 2040s and a big roll-out of hydrogen passenger vehicles after 2045. There is also a move towards hydrogen-fuelled buses and heavy goods vehicles during in the 2030s. These scenarios illustrate the considerable degree of uncertainty around the composition of the UK's future vehicle fleet, particularly in terms of the share given over to electric vehicles.

The key conclusion is that the way demand for heat and transport fuels is met is subject to uncertainties similar to those for primary energy supply and electricity generation., though there is perhaps more convergence over the absolute level of demand.

4.4 Implications

This section has shown that energy research planning needs to take into account a wide range of possible energy futures. The biggest divide is between: a) exploratory scenarios and 'reference cases' that foresee the energy future dominated by extensions of incumbent technologies and means of delivering energy; and b) normative scenarios which focus on what must be done if ambitious policy goals (notably on climate change) are to be achieved. However, 'new' energy technologies such as renewables and CCS play a role in all scenarios/projections, albeit with a lower market share and slower market penetration in reference scenarios. Therefore, a prudent approach to energy R&D would be to adopt a portfolio approach addressing both the development of new energy technologies and the improvement of the performance of incumbent technologies.

Recommendation. Energy R&D portfolios, especially those supported by bodies such as the research councils with a basic/strategic research remit with potential pay-offs in the long-term, should reflect significant uncertainties about the development of the energy system. It is not realistic to rely on the emergence of clarity regarding energy policy to guide research and training strategies.

Many 'new' technologies (e.g. wind, solar, bioenergy) have global potential and the UK may be able to compete in expanding international markets. However others, including marine renewables, may be more limited in their geographical scope and periodic review of the level and focus of support would be appropriate. Having a broad portfolio does not mean that all technologies should be supported indefinitely. Uncertainty has different implications for training provision and this matter is addressed in Section 7.3.

5. How well is the UK placed?

The UK spends relatively little on energy R&D in comparison to international competitors. The resources expended are out of alignment with ambitious energy and climate change policy goals. The research councils and other energy innovation bodies are in a position to press for a greater allocation of resources.

5.1 How much effort are we putting in?

The level of UK public support for energy RD&D, as reported to the IEA, has varied widely over the last few decades (Figure 10). Declines in the 1980s and early 1990s were associated with falling oil prices and the privatisation of energy utilities and national R&D laboratories. Public expenditure fell to a low of £30m pa in the early 2000s.[27]

Since the publication of the 2003 Energy White Paper budgets have risen again, but only to about one third of the levels of the 1970s and 1980s. The spike in 2010/11 reflects spending at the end of the last CSR period and capital spend associated with recovery from the recession.

Table 4 shows the estimated budget of £288m for 2012 broken down by research area. Investment in nuclear RD&D (22%), split almost equally between fission and fusion, has recently been overtaken by investment in energy efficiency (28%). Budgets for renewable energy RD&D (20%) are close to those for nuclear, with bioenergy and wind accounting for more than half of that total. Most of the £35m budget for fossil fuel research is focused on carbon capture and storage (CCS).

BOX 3: What does public sector RD&D cover?

R&D budgets, as reported to the IEA, are difficult to compare because governance structures (e.g. federalism versus centralised arrangements) vary across countries. The budgets reported to IEA by the UK cover the research councils, key government departments (DECC, BIS, DfT CLG) and other major funders such as the Energy Technologies Institute (ETI) and the Technology Strategy Board (TSB).

They do not include the Devolved Administrations or the former Regional Development Agencies (RDAs). Indirect support via the Higher Education Funding Council for England (HEFCE) and its counterparts in the Devolved Administrations is also excluded.

Reported budgets do not include support via Ofgem's RIIO (revenues = incentives + innovation + outputs) framework used to regulate electricity and gas transmission and distribution companies. This hybrid model encourages private energy companies regulated in the public interest to invest in RD&D. Projected support via RIIO (~£120m pa) greatly exceeds more traditional public support for energy network related research.

There are difficulties in attributing Research Council budgets to energy as cross-cutting research (for example in materials science) can make a significant contribution in the energy domain.

Figure 10: UK Annual Public Sector RD&D Budgets (£m, 2012 money)

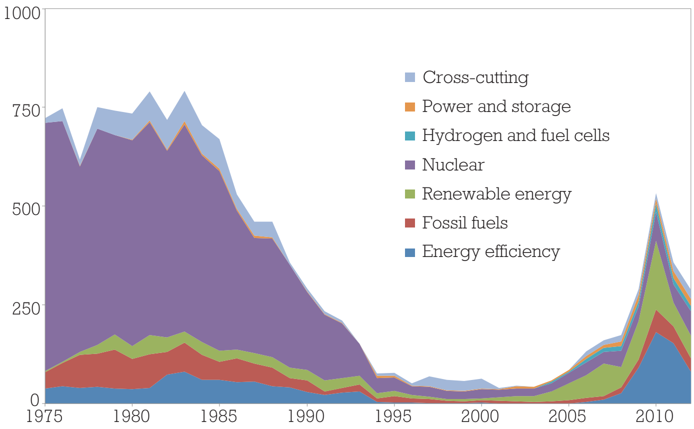
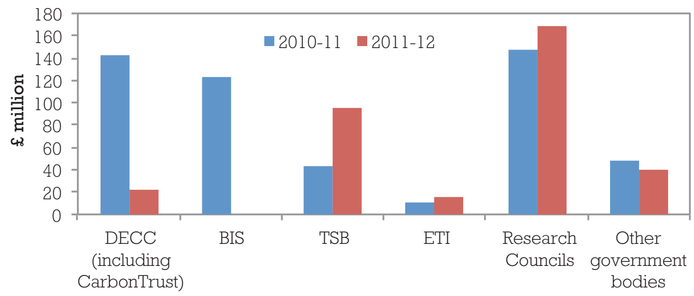


Figure 11 shows how expenditure on low carbon innovation was split between the main bodies in 2010-11 and 2011-12.[28] Research councils and TSB spend increased despite the overall fall reflected in Figure 10. The research councils accounted for 30% of the £522m spend in 2010-11 and almost half of the £351m spend in 2011-12. The fall in DECC spending is largely attributable to the changing role of the Carbon Trust. ETI's relatively low spend is because the organisation was still in the early stages of its development in the years in question.

Figure 11: Outturn spend by UK funding bodies on low carbon innovation



The setting of R&D budgets is as much an art as a science and there is no 'correct' level of spending. However, work conducted by the IEA[29] suggests that global energy RD&D investment would need to be raised by between a factor of three and six if increases in global temperatures are to be held within 2˚C above pre-industrial levels, the level of ambition endorsed by UK energy and climate policies.

[27] *The collection of data on energy RD&D is difficult (Box 3) and the figures provided are indicative.*

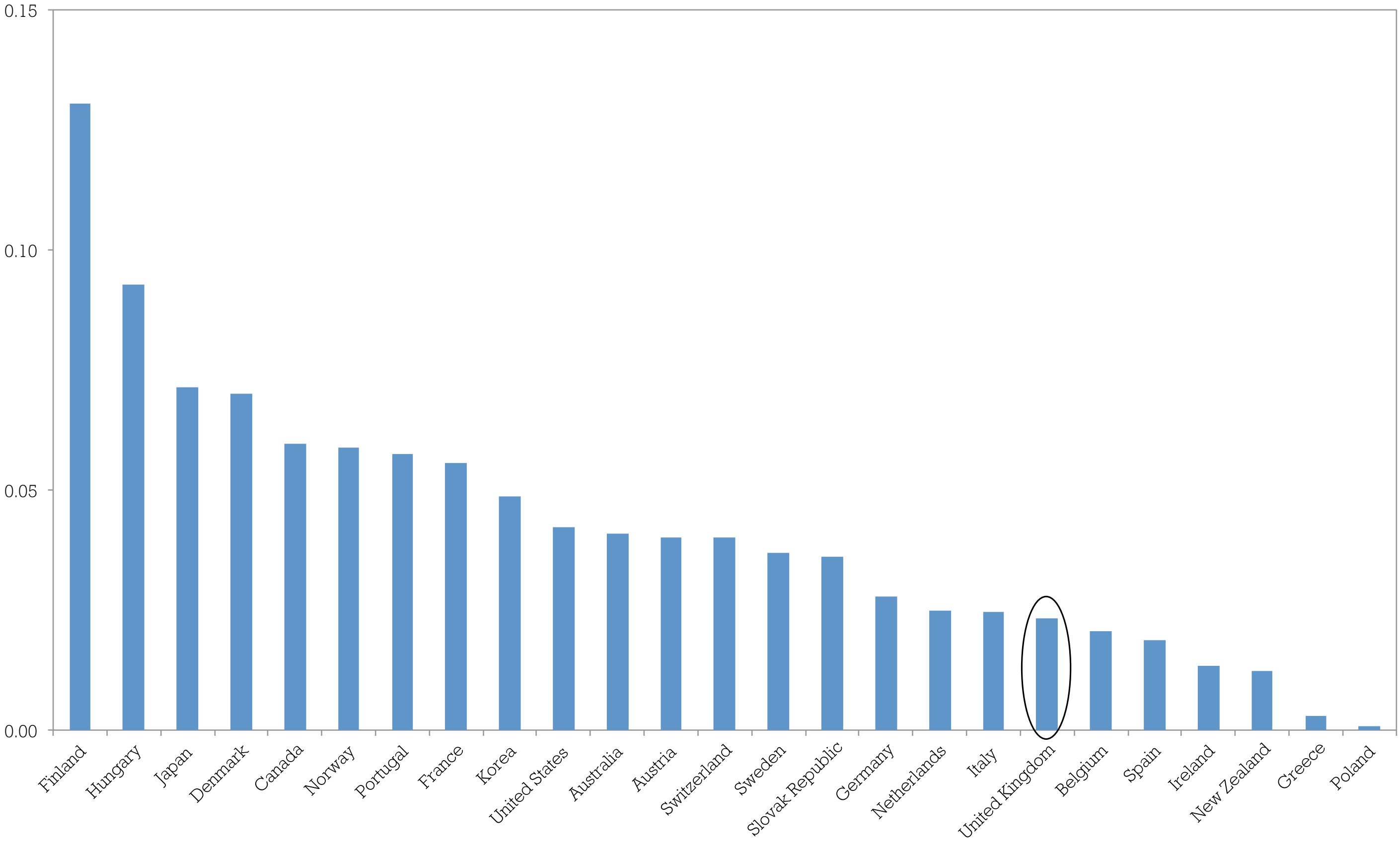
[28] *National Audit Office, Public funding for innovation in low carbon technologies in the UK: Briefing for the House of Commons Energy and Climate Change Select Committee, October 2013. http://www.nao.org.uk/wp-content/uploads/2013/10/Briefing-for-ECC-Public-funding-for-innovation-in-low-carbon-technology.pdf*

[29] *International Energy Agency, Tracking Clean Energy Progress 2013: IEA Input to the Clean Energy Ministerial, http://www.iea.org/publications/freepublications/publication/TCEP_web.pdf IEA*

Table 4: UK Public Sector Energy RD&D Budgets 2012 (£m)

Energy Efficiency, of which:	**80.2**	**28%**
Industry	2.8	3%
Buildings, appliances and equipment	16.3	20%
Transport	50.7	63%
Other energy efficiency	10.4	13%
Fossil Fuels, of which:	**34.8**	**12%**
Oil and gas	4.0	11%
Coal	8.5	24%
CO2 capture and storage	22.4	64%
Renewable Energy Sources, of which:	**56.9**	**20%**
Solar energy	9.7	17%
Wind energy	15.8	28%
Ocean energy	9.4	17%
Biofuels (incl. liquids, solids and biogases)	20.1	35%
Hydroelectricity	0.1	0%
Other renewable energy sources	1.1	2%
Unallocated renewable energy sources	0.6	1%
Nuclear, of which:	**62.3**	**22%**
Nuclear fission	30.4	49%
Nuclear fusion	31.9	51%
Hydrogen and Fuel Cells, of which:	**13.4**	**5%**
Hydrogen	3.5	26%
Fuel cells	9.9	74%
Other Power and Storage Technologies, of which:	**17.3**	**6%**
Electric power conversion	0.2	1%
Electricity transmission and distribution	12.4	72%
Energy storage	4.7	27%
Other Cross-cutting Technologies/Research, of which:	**23.0**	**8%**
Energy system analysis	4.4	19%
Basic energy research not allocated	11.4	50%
Other	7.2	31%
TOTAL	**287.9**	**100%**

Figure 12: Public Sector Energy RD&D Budgets 2011 (% of GDP)



UK energy RD&D budgets are below the global average. Following the peak at the start of the current CSR period, the UK has fallen back to 19th position in the IEA rankings and 14th within Europe in terms of energy RD&D spend per unit of GDP (Figure 12). In its 2012 *Review of the UK*, the IEA noted that "the levels of spending do not seem to match the UK's ambitious climate policy objectives and its world-renowned academic institutions and capability" and recommended that "the UK acknowledge and publicly fund at world-class levels a focused energy RD&D programme to catalyse a broader United Kingdom innovation agenda that reflects the country's industrial and intellectual comparative advantage"[30]

The UK would need to increase its current public sector energy RD&D spend by 70% to bring itself back to the median level of IEA countries, and by 200% to bring itself to the front rank. Further increases would be necessary if global energy RD&D budgets were to be aligned with the 2°C climate change objective and, implicitly, UK climate policy.

Recommendation. Acknowledging public expenditure constraints, the research councils and other research and innovation bodies should press for public expenditure settlements that are better aligned with the UK's wider climate change and energy policy ambitions.

The UK contributes to the EU Framework Programme (FP) budget from which UK companies and scientists receive support in return. In the early stages of FP7 (when 18% of the budget had been allocated), the UK had been allocated about 14.6% of the total EU budget, roughly in line with GDP and one third higher than average in per capita terms.[31] UK Higher Education Establishments (HEIs) received 61% of funds coming back to the UK across all fields (EU average 39%), commercial organisations 22% (EU average 26%) and research organisations 11% (EU average 26%). This mirrors wider perceptions about the strengths of UK science, greater weaknesses on the industrial side and the run-down of R&D facilities in the 1990s. Energy represented one of the weakest areas of UK performance with only €28.5m (9% of the available budget to that point) being allocated to the UK. This is under £20m in annualised terms and is small in comparison with domestic R&D spend.

Private sector R&D is much harder to assess. Table 5, based on the EU R&D scoreboard,[32] shows that five of the top ten R&D companies in the European energy sector are in the oil and

[30] *International Energy Agency, Energy Policies of IEA Countries: 2012 Review of the UK, http://www.iea.org/w/bookshop/add.aspx?id=424*

[31] *Technopolis Group, The impact of the EU RTD Framework Programme on the UK, May 2010, http://ec.europa.eu/research/evaluations/pdf/archive/fp7-evidence-base/national_impact_studies/impact_of_the_eu_rtd_framework_programme_on_the_uk.pdf*

[32] *http://iri.jrc.ec.europa.eu/scoreboard12.html*

Table 5: Top ten companies for R&D in the European energy sector 2011

Company	Country	Industry	R&D 2011 (€m)	R&D intensity (% of sales)
Royal Dutch Shell	UK	Oil & gas producers	869.5	0.2
Total	France	Oil & gas producers	776.0	0.5
Electricite de France	France	Electricity	518.0	0.8
BP	UK	Oil & gas producers	491.5	0.2
AREVA	France	Electricity	434.0	4.9
Vestas Wind Systems	Denmark	Alternative energy	393.0	6.7
Statoil	Norway	Oil & gas producers	283.4	0.3
RWE	Germany	Gas, water & multiutilities	235.0	0.5
GDF Suez	France	Gas, water & multiutilities	231.0	0.3
ENI	Italy	Oil & gas producers	191.0	0.2
ALSO				
Iberdrola (11th)	Spain	Electricity	136.4	0.4
E.ON (14th)	Germany	Electricity	108.0	0.1
SSE (21st)	UK	Electricity	56.5	0.1

Source: EU R&D scoreboard

gas sector, with the UK/Netherlands Royal Dutch Shell company heading the list. The combined R&D spend of Shell and BP at €1.4bn exceeds not only UK public sector RD&D spend on fossil fuels, but the entire public sector energy RD&D budget, by a factor of four. The Shell/BP figures cover R&D expenditure worldwide and, whilst it includes some spending in universities, direct comparisons are difficult. However, it provides robust evidence that, in the fossil fuel sector and especially in oil and gas, the private sector dominates R&D. Oil companies appear to spend 0.2-0.5% of turnover on R&D.

Electricity companies and multi-utilities account for four of the top ten companies. The two biggest spenders are EDF and AREVA both of which have large nuclear interests. AREVA spends nearly 5% of its turnover on R&D. Other electricity companies and utilities tend to be in the range 0.1-0.4%, including SSE which lies at 21st place in the European scoreboard.

The only alternative energy company to make the top ten is the wind manufacturer VESTAS. Engineering companies with diverse interests across energy and other sectors (e.g. Siemens, Alstom) also contribute to energy R&D but are not shown in Table 4.

5.2 How well do we perform?

Directing funding towards energy R&D does not by itself guarantee productive outcomes. Assessing the capability to deliver productive outcomes inevitably involves more subjective judgments.

The view of the International Panel that reviewed the RCUK Energy Programme was that "across almost all areas reviewed by us we found interesting, leading edge and world class research. The excellent international reputation of UK research is deservedly earned". However, they noted that not all of the research was of a uniform high standard without identifying specific areas. The IEA remarked on "world-renowned academic institutions and capability".

A number of recent reports and activities have addressed: the benefits to the UK of investing in energy R&D; growth and competitiveness implications; the relevance of technologies to UK energy policy goals; industrial and scientific capabilities; and appropriate technology strategies. Table 6 draws these sources of evidence together.

The workshops convened during the preparation of this report assessed, subjectively, the UK's scientific and industrial capabilities in a number of technology areas, as well as their relevance to UK energy futures.[33] These three judgments have translated into low/medium/high indicators in Table 6.

The TINAs produced by LCICG review the potential deployment of a range of technologies, both globally and in the UK. The TINAs also identify the potential business value to the UK and the reduction in energy system costs associated with having individual technologies available. The reduction in energy system costs is based on the premise that the UK meets its objective of reducing GHGs by 80% by 2050. Any relaxation of, or failure to meet, the target would reduce the benefits.

The Committee on Climate Change (CCC) divided technologies into three groups for which different strategies would be appropriate:

Develop and deploy. Where the UK has a full range of manufacturing and business R&D facilities, the UK should offer a full range of support across the innovation chain. This could include basic research of an application-inspired character.

Develop. Where the UK lacks production advantages, the UK should focus on demonstration and adapting technologies to local circumstances. There is less of a case for basic research in these areas.

Research and develop. For less mature technologies, or those where there is no clear advantage for any country, basic research should be less directed but the results should be exploited with a view to development, demonstration and deployment. This is more compatible with a science-inspired approach.

Table 6 also shows in which direction EPSRC intends to change support for specific technologies in terms of grow, reduce or maintain. The high-level messages from Table 6 follow. Section 6 explores opportunities associated with specific areas of energy research in more depth.

- In general, more technologies are associated with high scientific capabilities than with high industrial capabilities. This reinforces evidence from the International Review Panel and performance in the EU Framework Programmes.
- The highest correlation between industrial and scientific capabilities comes in technologies with an 'offshore' dimension – oil and gas, offshore wind and marine renewables (ocean energy). Offshore renewables also align with the CCC's 'develop and deploy' strategy. However, ocean energy is seen as less relevant to the UK's energy future and the TINAs indicate that levels of deployment and economic benefit could be less than for other low-carbon generation technologies such as offshore wind and nuclear, or even zero.
- Few technologies are associated with low scientific capabilities but those that are include: industrial energy demand (other than industrial CCS), district heating, heat pumps, hydropower and geothermal energy, and perhaps more controversially, nuclear fission.

[33] *https://workspace.imperial.ac.uk/rcukenergystrategy/Public/reports/Strategic%20Workshop%20Reports/Energy%20strategy%20fellowship%20Report%202%20-%20Energy%20strategies%20and%20energy%20research%20needs%20final.pdf1*

- In the less mature technology areas for which the CCC recommends a science-inspired 'research and develop' strategy, scientific capabilities are generally viewed as high. These include solar PV, hydrogen, fuel cells, and, at a slightly lower capability, energy storage. In most of these areas, the application of materials science is essential. EPSRC's intention of reducing support for hydrogen appears to reflect lower industrial capability and value in terms of the UK's energy future.
- The Department of Business, Innovation and Skills' (BIS's) only 'great technology' in the energy field – energy storage – is characterised by mid-level scientific and industrial capabilities. However, other 'great technologies' of a more cross-cutting nature such as big data, materials science and biosciences have potential applications in the energy field.

The highest correlation between industrial and scientific capabilities comes in technologies with an 'offshore' dimension – oil and gas, offshore wind and marine renewables.

Table 6: The UK's scientific and industrial energy capabilities and future energy needs

	Energy Strategy Fellowship				TINAs deployment (GW)		TINAs economic benefit (£bn)		CCC	EPSRC
	Scientific capability	**Industrial capability**	**Relevance**	**Readiness[1]**	**UK**	**Global**	**Cost reduction[2]**	**Value to UK[3]**	**Strategic response**	**Direction of funding**
Energy Efficiency		-	-	-	-	-	-	-	-	Grow
Industry	L	L-M	M	3.5	-	-	17-32	1.5-6.5	R&D/Deploy[4]	-
Buildings	H	M	H	4.9	-	-	-	-	Deploy	maintain
District heating	L-M	L	M	-	10-95	680-1000	2-15	6.8	-	-
Heat pumps	L-M	L	M	-	70-240	1211-4130	11-39	24	-	-
Transport	M-H	L-M	H	5.6	-	-	-	-	Develop/deploy	reduce
Coal	L-M	M	M	4.9	-	-	-	-	-	reduce
Oil and gas	H	H	H	4.9	-	-	-	-	-	reduce
CCS	H	M	H	4.9	11-60	202-1011	10-45	3-16	D&D	maintain
Solar	H	L-M	M	5.2	-	-	-	-	R&D	maintain
Wind	H	M	H	6.0	-	-	-	-	-	maintain
Offshore wind	-	-	-	-	20-100	119-1142	18-89	7-35	Develop/deploy	-
Ocean energy	H	H	M	6.0	0-13	0-240	0-8	0-4	Develop/deploy	maintain
Bioenergy	H	M	M-H	6.3	278-2586(PJ)[5]	12-151 (EJ)	6-101	6-33	-	maintain
Other renewables				-	-	-	-	-	-	-
Nuclear fission	M	L-M	M-H	-	16-75	500-2000	2-14	1.5-13	Develop/deploy	maintain
Nuclear fusion	H	L	L-M	-	-	-	-	-	-	-
Hydrogen	H	L-M	M	-	-	-	-	-	R&D	reduce
Fuel cells	H	M	L-M	5.2	-	-	-	-	R&D	Maintain
Energy networks	M-H	M-H	M-H	4.5	-	-	0.4-1.1	1.5-3.6	-	maintain
Smart grid	-	-	-	4.5	-	-	1.7-7.4	3.4-25.7	Develop/deploy	-
Energy storage[6]	M	M-H	M-H	-	7-59	-	1.9-10.1	1.4-4.7	R&D	grow
Energy systems analysis	H	M-H	H	-	-	-	-	-	-	grow

__Notes:__ 1) "readiness" was a subjective measure of how workshop participants, on a scale of 0-10, thought the UK stood in terms of research capabilities to tackle future energy challenges; 2) the reduction in the cost between now and 2050 of meeting the UK's 80% GHG target if the technology is available; 3) contribution to UK GDP through participation in UK and global markets; 4) 'R&D' for industrial CCS, 'deploy' otherwise; 5) 1,000 PJ = 1 EJ per annum is equivalent to 32GW of power; 6) one of the eight 'great' technologies identified by BIS.

6. Research needs and priorities

The UK has scientific strengths in many areas of energy research but fewer industrial strengths. Industrial and scientific strengths are best aligned for energy demand and, building on the legacy of North Sea oil and gas, technologies deployed offshore. In application-led research areas, priorities should reflect prospects for technology deployment.

6.1 Industrial energy

Industrial energy is intrinsically an applied area of research where collaboration between academic researchers and industry is essential. There is agreement within and outside the industrial energy research community that there are weaknesses in this area in the UK. These are reinforced by a number of factors including:

- historic declines in many manufacturing sectors;
- the prevalence of overseas ownership resulting in R&D facilities being located outside the UK; and
- academic reward systems that place less emphasis on applied research achievements.

Research needs in this area fall into two broad classes:

- More traditional engineering-based industrial energy research focusing on incremental and radical process improvements. The UK has both less need and less capability in this area compared to countries retaining a larger manufacturing base.
- 'Whole systems' perspectives including materials flows, product design and the nature of economic interactions between sectors. UK competences in these areas received a substantial amount of attention in the expert workshop which we convened.

There is a robust case for the research councils continuing to support 'whole systems' type research in the industrial energy field, for example through the new EUED InDemand Centre. Related investments, notably the Innovative Manufacturing Initiative, may also contribute to this type of research. Continuing dialogue between EPSRC and ESRC is needed to support research in this area.

Recommendation. 'Whole systems research' focusing on industrial energy systems, their wider role in the economy and links to materials flows should continue to be supported through collaboration between EPSRC and ESRC.

The case for directed support for more traditional industrial energy research is less clear. If support for this type of research were to be increased, it would require managed mode funding and perhaps the appointment of a 'research champion' to reinforce links with industry and the policy world. Collaboration with innovation bodies supporting more applied R&D would be important if this approach were taken.

The alternative approach for the research councils, especially EPSRC, would be to continue to improve scientific capabilities in underpinning areas of research that have potential application both inside and outside the industrial energy domain. These include catalysis, materials science and the modelling and simulation of fluid flows. The scientific community could then collaborate with industry on a more *ad hoc* basis, supporting bids into initiatives led by bodies such as TSB as and when necessary. Regardless of whether a directed or more hands-off approach is adopted, better mechanisms for supporting links between the academic and industrial communities would increase the impact of research activity.

Recommendation. The case for directed support for industrial process energy research is relatively weak. EPSRC should provide support through broader manufacturing initiatives and responsive mode. The relevant research communities should be encouraged to take up these opportunities and establish suitable links with industrial partners.

6.2 Energy in the home and workplace

Energy demand in the residential and commercial sectors is likely to stay relatively flat even in business-as-usual scenarios in the UK, and could fall if energy efficiency and climate change policies are successful. A business-as-usual scenario would see a continued dependence on natural gas for heating purposes. Complying with the EU Renewable Energy Directive (RED) will require the greater use of biomass and electrically-vectored technologies, such as heat pumps. Most long-term low-carbon scenarios envisage a substantial degree of electrification of heating. Electricity demand is likely to increase in any event because of demand from IT and appliances.

The International Review Panel judged that research on demand reduction needed a higher profile in the overall research portfolio. Recent support for Energy End Use Demand (EUED) centres has begun to redress this balance.

The main research challenges appropriate for research council support fall into four areas:

- building energy technologies;
- energy consumption behaviour;
- governance and business models for energy supply; and
- socio-economic systems analysis.

Much of the research will need to focus on transforming physical aspects of the home and workplace through the introduction of innovative construction materials, building designs and retrofit solutions. Energy demand management, decentralised generation and smart technologies could alter patterns of demand in more transformative ways.

The social sciences have a significant role to play in helping to understand lifestyles and patterns of energy consumption behaviour and to identify ways of shaping these patterns. In practice, the technical and social research challenges are intertwined. An interdisciplinary approach to research in this area is therefore needed. The development of alternative governance arrangements, innovative business models and new modes of consumer engagement are also important areas for research.

All of this research is relevant at scales ranging from the individual level through to the household, community, city and national levels.

Recommendation: Building on recent research investments, the research councils need to continue directing resources towards building energy technologies, energy consumption behaviour and business models for energy supply. Given the socio-technical nature of the research challenge in the area of energy demand, it is important that research is sensitive to technical aspects, social aspects and their interaction.

The majority of research funded in this area has focused on energy consumption in the home rather than the workplace. There is a pressing need for research into the factors responsible for characterising commercial energy consumption behaviours and which interventions could shape this behaviour.

Recommendation: A greater emphasis needs to be given to research aimed at understanding energy consumption in commercial environments.

6.3 Transport energy

Transport energy demand accounts for more than a third of the UK's final energy demand, though the absolute level is projected to fall across a range of scenarios. There is a wide difference in character between business-as-usual energy scenarios which foresee a continuing dominant role for fossil fuels for surface transport, and normative low-carbon scenarios which envisage greater penetration of biofuels, plug-in hybrid/electric vehicles and/or hydrogen- fuel cell vehicles in the longer term.

Research in the area of transport energy demand is difficult to disentangle from transport research more generally. Individual researchers or teams tend to focus on specific modes such as road transport, aviation and shipping. Some relevant research is focused at the level of vehicles, aircraft and ships while other research is at the transport system level. As a result, there is no single community that operates under the banner of transport energy research. This led to a more fragmented set of research priorities than usual being identified at our transport energy workshop.

The research challenges identified fall into eight categories:

- automotive transport;
- aviation;
- transport fuels;
- freight and logistics;
- transport energy behaviour;
- transport energy policies and business models;
- transport planning and infrastructure; and
- understanding, measuring and modelling transport system change.

Whilst some of these research areas are primarily engineering focused, such as automotive transport, and others are more social science focused, such as transport energy policies and business models, they are all to some extent socio-technical in character. This emphasises the importance of considering both technical and social aspects when researching specific transport energy issues, such as *transport planning and infrastructure* or *freight and logistics.*

The spatial scale of the research challenges range from specific technological components and individual travel behaviour through to system-wide infrastructure issues and system change. Detailed research into critical system components needs to be sensitive to the broader system context and relationships with other system components.

Recommendation: Given the socio-technical nature of transport energy research challenges, it is important that interdisciplinary research should be supported, covering technical aspects, social aspects and their interaction. Research challenges need to be formulated across a range of spatial scales to provide a stronger 'whole system' understanding of the transport energy system.

A recurring theme at the workshop was the need to be sensitive to the difficulties associated with radical changes to the transport energy system due to a range of lock-in effects associated with sunk investments, embedded infrastructure and engrained transport behaviours. This underlines the importance of innovative solutions that make the most of existing transport and infrastructure. At the vehicle level, these include efficiency improvements for conventional petrol/diesel powered vehicles and retrofitting existing vehicles to become more energy efficient. At the system level, it covers the integration of new vehicle technologies, such as those that enable the use of autonomous vehicles on existing roads, into existing infrastructure.

Recommendation: Research should focus not only on novel transport energy technologies and infrastructures but also on improving the effectiveness of existing ones.

6.4 Fossil fuels and carbon capture and storage

The dominant role of fossils fuels in both the UK's and the global energy system is expected to continue for some time yet. In the longer term (2030-50), the role of fossil fuels in energy systems is much less certain and even contested. The biggest differentiator in terms of scenarios is whether or not the UNFCCC climate objective of keeping global temperature increases below 2˚C above pre-industrial levels is realised. Fossil fuel use would need to contract significantly if the goal is to be met; if not, the use of fossil fuels, notably gas and coal, is likely to increase significantly at the global level. CCS technology can help to reconcile climate policy goals and the use of fossil fuels.

The UK has high levels of scientific and industrial capability in relation to oil and gas, reflecting the legacy of North Sea development. CCS could potentially play a major role in the UK given climate policy ambitions. The UK is believed to have high scientific capabilities in relation to CCS but a rather weaker industrial capability. Skills in the geological sciences are applicable in a number of domains (conventional and unconventional oil and gas extraction, carbon storage, nuclear waste storage and geothermal energy).

Recommendation. The research councils should build on the UK scientific strengths and hedge against uncertainties concerning the future role of fossil fuels by investing in research relevant to fossil fuel extraction, especially from unconventional fossil fuel resources, and in CCS research. The science underlying fossil fuel conversion and use is at a more mature stage and is less of a priority for research council support.

Research priorities in this area fall into three broad categories:

- energy activities in the sub-surface;
- carbon capture, storage and utilisation; and
- cross-cutting challenges.

The main sub-surface challenges relate to: understanding the unconventional gas and oil resource base; understanding how physical resources translate into economically recoverable reserves; residual reserves of conventional coal, oil and gas; security and safety issues related to methane; and methane hydrate resources.

The CCS challenges are varied and cover the full chain from capture to storage. There are more basic research challenges associated with: small-scale carbon capture; negative emissions technologies (BECCS); membranes, adsorbents and capture looping; air capture; and biomimetic CO_2 capture. The research community can also contribute to more near-term challenges including: capture retrofit of gas-fired generation; reliability, availability, maintainability and operability (RAMO); and monitoring and control.

The range of underpinning research challenges is wide. In the geosciences, these include understanding fluid-rock interactions; characterising complex subsurface systems at large spatial and temporal scales; and the impacts of engineered activity on the deep sub-surface. There are socio-economic challenges associated with public engagement in relation to sub-surface activities and legal/regulatory issues associated with storage. Understanding the impacts of novel methods of energy extraction and CCS on the environment and ecosystem services is another priority area.

Recommendation. The research councils should prioritise three broad categories of research across the fossil fuel/CCS domain: energy-related activities in the sub-surface; carbon capture, storage and utilisation; and cross-cutting challenges relating to the geosciences, socio-economic aspects and environmental impacts.

6.5 Electrochemical energy technologies and energy storage

Electrochemical energy technologies cover a wide range including: solar PV; fuel cells; hydrogen production and storage; batteries; super-capacitors; and hybrid storage. Our workshop in this area also covered other energy storage technologies, such as flywheels and compressed air. There are many synergies between different electrochemical technologies which, in general, are underpinned by the materials sciences.

Building on the evidence gathered for this report, a cross-cutting strategic framework would help to establish major challenges in the electrochemical area and identify areas of potential collaboration between research groups.

Recommendation: A strategic framework, linking different electrochemical energy technologies in terms of research needs, skills and shared infrastructure, should be created. This framework should be utilised when planning research programmes in order to identify potential synergies in research capabilities and to maximise collaborative efforts.

The research challenges identified in this sector fell into four areas:

- photovoltaics;
- fuel cells and hydrogen;
- batteries and other electrochemical technologies; and
- broader issues and underpinning challenges.

Research challenges identified in photovoltaics include: new materials for PV devices; low-cost manufacturing for new PV technologies; scalable, low-cost thin-film deposition methods; the integration of PV into hybrid electrochemical systems; and research into building-integrated PV modules.

Challenges relating to fuel cells and hydrogen range from the fundamental to the applied. These include: greater fundamental understanding of materials and interfaces; understanding the degradation of catalysts and membranes over time; new, more abundant materials for catalysts and electrodes; methods to measure and understand device performance whilst in operation; increasing the lifetime and durability of devices; and substantial cost reductions in materials and manufacturing.

Energy storage technologies, including batteries, supercapacitors and other technologies, face several major research challenges including: further research and development of lithium-ion and lithium-air batteries; research into hybrid batteries/super-capacitor systems; research into lossless capacitors for short- and medium-term charge storage; and improving materials and lowering the costs for thermal storage systems.

Broader and underpinning research challenges for electrochemical energy technologies include: increasing efficiency; lowering the cost of production; improving the size and weight of devices; and identifying more abundant, environmentally friendly and cheaper materials.

Basic research in physics, chemistry and materials science underpins research into electrochemical technologies. 'Blue-skies' research can ensure that the UK retains a competitive scientific edge in these areas.

Recommendation: The research councils should continue to fund basic 'blue skies' research into electrochemical energy phenomena, for example through the EPSRC materials for energy research area, as well as more applied research.

6.6 Wind, wave and tidal energy

Wind, wave and tidal stream energy are distinguished by the combination of mechanical, civil and electrical engineering expertise on which they depend. Offshore wind, wave and tidal energy are exploited in the marine environment where the UK has accumulated a great deal of expertise as a result of the exploitation of North Sea oil and gas reserves. However, onshore wind, the most mature of the technologies, currently makes the largest contribution to electricity generation, albeit only around 5% of the UK total. Investment in offshore wind is proceeding rapidly, but the technology is still at a less mature level than onshore wind. There has been little investment so far in wave and tidal, the least mature technologies. However, a major engineering company has recently invested in tidal stream technology suggesting that it holds commercial promise.

The UK's National Renewable Energy Action Plan[34] anticipates about 28 GW of wind energy being on the electricity supply system by 2020, split fairly evenly between onshore and offshore, and about 1300 MW of tidal/wave energy. Beyond 2020, there is a great deal of uncertainty about deployment. Wind energy production largely depends on deployment polices. Previous projections of marine energy deployment have proved to be over-optimistic and wave technology in particular is perhaps less mature than has previously been perceived. The TINA on marine energy sees a very wide range of potential deployment by 2050, with zero deployment being possible. The value of research into wave and tidal energy depends on prospects for commercial deployment and these should be kept under review.

Research challenges in the wind, wave and tidal area tend are generally of an applied character since even the more basic research tends to be application-inspired. The following priority areas have been identified:

- device and array design;
- foundations and support structures;
- grid integration;
- system reliability;
- asset management;
- monitoring environmental impacts;
- resource assessment; and
- economic, social and governance factors.

[34] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/47871/25-nat-ren-energy-action-plan.pdf

The first four categories have a strong technology and engineering focus. They are concerned with improving the performance and reliability of technologies at multiple scales, for instance device components, devices, device 'fixings', arrays and array-grid integration.

Research on *Asset management*, which includes condition monitoring, needs to cover communication and ICT issues in order to maximise performance though appropriate management. Monitoring environmental impacts is concerned with investigating how the deployment of technologies will impact the environment and the provision of ecosystem services. Most of the recommendations related to the marine environment. *Resource assessment* is concerned with assessing the extent and distribution of wind, wave and tidal resources in the UK at various spatial and temporal scales. It is acknowledged that research into the governance and planning of wind, wave and tidal development, and the associated economic and social factors is of importance.

Recommendation: Research is needed on a range of technical issues relating to wind, wave and tidal energy. A key challenge is to understand how technologies operating at different scales (component – device – array – ecosystem) link together. Given the applied nature of many of the research challenges, close linkages with other innovation bodies such as TSB and ETI are essential.

A number of these research challenges can be framed so as to generate valuable research outputs for both the offshore wind and marine energy sectors. For instance, research into connecting offshore wind or marine energy arrays to the national grid raises similar issues.

Recommendation: Further consideration should be given to the social, economic, environmental and planning/policy issues that relate to wind, wave and tidal energy

6.7 Bioenergy

The role of bioenergy in energy systems is controversial. The level of sustainable supply is linked to uncertainties about the lifecycle GHG emissions of bioenergy chains and competition for land that might otherwise be used for food production. The UK's Bioenergy Strategy[35] foresees bioenergy's share of primary energy supply rising from less than 5% now, to around 10% in 2020 and peaking in the rage 13-23% in the 2040s before falling back to 8-22% by 2050. UK demand would be met by a mixture of domestic production and imported biomass.

Second generation bioenergy production from lignocellulosic biomass (from plant cell walls) offers advantages in sustainability terms compared to the use of food crops for energy production. The key research challenges relate to the production, processing, conversion and use of second generation biofuels. The potential for domestic bioenergy to contribute to UK energy demand and the growth and competitiveness agenda are key drivers of UK research.

Bioenergy is a particularly complex domain as it constitutes an energy sub-system, comparable with the existing fossil fuel system, rather than being a term describing a single technology or fuel. Bioenergy draws on many areas of science. BBSRC and EPSRC have the strongest interests covering crop production and improvement (BBSRC) and processing and conversion (EPSRC and BBSRC). NERC has interests relating to land use and sustainability impacts. Systems aspects and logistical issues such as harvesting and transport are of interest to EPSRC and ESRC. Biomass can be used for a variety of non-food purposes and BBSRC's interest is framed by a wider grand challenge on *Industrial biotechnology and bioenergy.*

The UK has scientific strengths in bioenergy, especially in relation to crop production and improvement. The UK is seen to be weaker in terms of industrial strengths and application. The research councils have made two significant investments in bioenergy: the BBSRC Sustainable Bioenergy Centre (BSBEC) and the SUPERGEN Bioenergy Hub (EPSRC). BSBEC is strong in terms of fundamental science whereas SUPERGEN Bioenergy has a more applied orientation. Both enjoy good links with industry.

There have been gaps in the research council bioenergy portfolio. ETI has supported a project on Ecosystem Land-Use Modelling (ELUM) which involves: a) an empirical study of the impact of bioenergy crop land-use changes on soil carbon stocks and GHG emissions; and b) the development of a model to assess quantitatively changes in levels of carbon, nitrogen and water in soil, and GHG fluxes. This basic science was arguably in the research council domain.

The bioenergy portfolio supported by the research councils is widely seen to be insufficiently joined up. There is strong case for joint BBSRC/EPSRC support for interdisciplinary programmes and projects as well as more systematic interactions between major investments, as is the case for nuclear and CCS.

Recommendation. The research councils, especially BBSRC and EPSRC, should seek to integrate better their research investments and should consider joint funding of programmes and projects. Greater clarity about the orientation of research council energy strategies in terms of the balance between basic and applied research would be helpful to both the research community and users.

Bioenergy research priorities fall into four main categories:

- resilient energy crops;
- land use and sustainability;

[35] *DfT/DECC/Defra, UK Bioenergy Strategy, April 2012. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48337/5142-bioenergy-strategy-.pdf*

- carbon and economic optimisation; and
- commercialisation aspects.

Under *resilient energy crops*, the development of sustainable, high-yielding energy crops is a priority, especially crops suitable for growing on low-grade/marginal land in order to avoid food-fuel conflicts. Minimisation of water use is another priority. Crops should also be resilient to extreme weather events and future climate change. There needs to be a joined up approach between those working on crop improvement and those working on processing and conversion so that crop attributes are developed with a view to application. Under *land use and sustainability*, the food/energy/land use/water nexus needs to be systematically explored. Whole systems analysis of land use changes and impacts on the provision of ecosystem services is required. Developing negative carbon emission technologies such as bioenergy and carbon capture and storage (BECCS) could make an important contribution to meeting climate goals in the long-term. Proving the technical viability of large-scale BECCS is a research priority. Understanding how technology can be adapted to take account of local conditions and environmental constraints will assist with the commercialisation of bioenergy chains.

There is a particular need for longer-term research horizons in the bioenergy field if a full scientific understanding of the consequence for crop production in terms of soil changes and GHG emissions is to be gained. Research needs to be linked to crop trials.

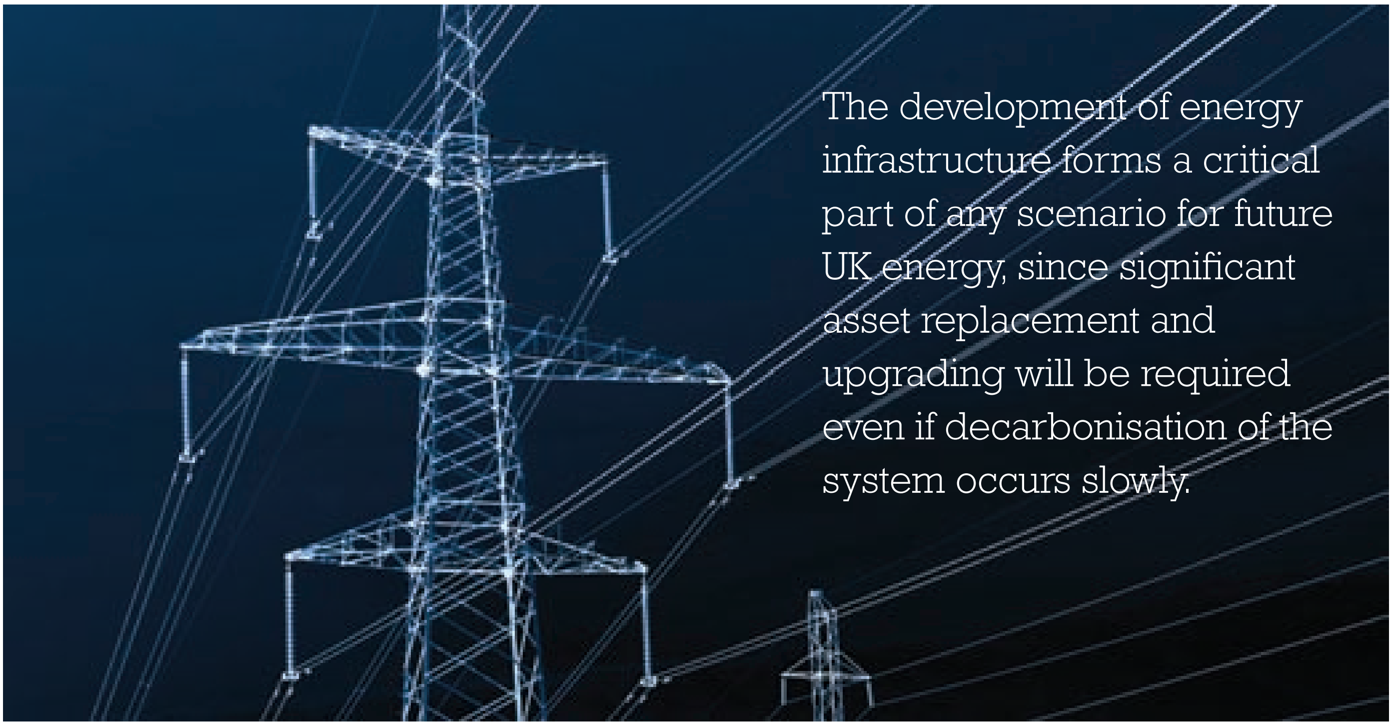
Recommendation. The research councils should continue to support a broad portfolio of research in the bioenergy field and should make efforts to ensure that research is linked to field trials and monitoring activities. Longer-term research support, perhaps ten years, with a five year breakpoint might be appropriate for research linked to field trials.

6.8 Nuclear fission

Priorities for nuclear R&D have been the subject of several recent reviews. These include the Government's Nuclear Industrial Strategy[36] and the Review of the Civil Nuclear R&D Landscape[37]. We did not duplicate these efforts which form a critical part of the evidence base for future research priorities. The Fellowship team ran a side-meeting at the 2013 meeting of the Nuclear Universities Consortium. The outputs from that session have been incorporated in the cross-cutting conclusions in Section 7.

6.9 Energy infrastructure

The development of energy infrastructure forms a critical part of any scenario for future UK energy, since significant asset replacement and upgrading will be required even if decarbonisation of the system occurs slowly. The increasing quantities of intermittent low-carbon and distributed generation found in many decarbonisation scenarios would require a substantial reworking of the UK's infrastructure to handle new patterns of energy flows, with most resource required for the electricity networks.



[36] *BIS/DECC, 'Nuclear Industrial Strategy: the UK's nuclear future', 2013, https://www.gov.uk/government/publications/nuclear-industrial-strategy-the-uks-nuclear-future*

[37] *BIS/DECC 'A review of the Civil Nuclear R&D Landscape in the UK', 2013, https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/168039/13-631-a-review-of-the-civil-nuclear-r-and-d-landscape-review.pdf*

There are significant research questions relating to the structure and extent of decentralisation of future networks.

The UK has a strong scientific capacity in electrical networks, with research in power systems engineering described as world leading. Scientific capabilities in heat networks and CO_2 transportation are somewhat weaker. Industrial capabilities in electrical networks are also strong, and the launch of the Low Carbon Network Fund (LCNF) and the new RIIO price controls, both managed by Ofgem, are channelling substantial quantities of resource into innovation and demonstration projects in this area. UK academics and research institutions contribute significantly to many LCNF projects. The balance of time that UK academics devote to basic research as opposed to applied research/ consultancy work under the LCNF needs consideration.

Recommendation: The research councils should work with Ofgem and other late-stage innovation funders to ensure that Research Council-funded programmes complement and provide basic underpinning research for demonstration and deployment projects. The roles and responsibilities of the research councils and other innovation bodies along the innovation chain should be clarified.

Research priorities fall into three broad categories:

- systems planning and operation;
- policy design and market design; and
- component technologies.

Major challenges in systems planning and operation include: ensuring reliability of supply and robustness of energy systems; system control and coordination; balancing supply and demand; ICT integration into monitoring and coordination; integration of different energy vectors and networks; characterising the risks and mitigation efforts of cyber-security; and minimising the environmental impacts of infrastructure projects.

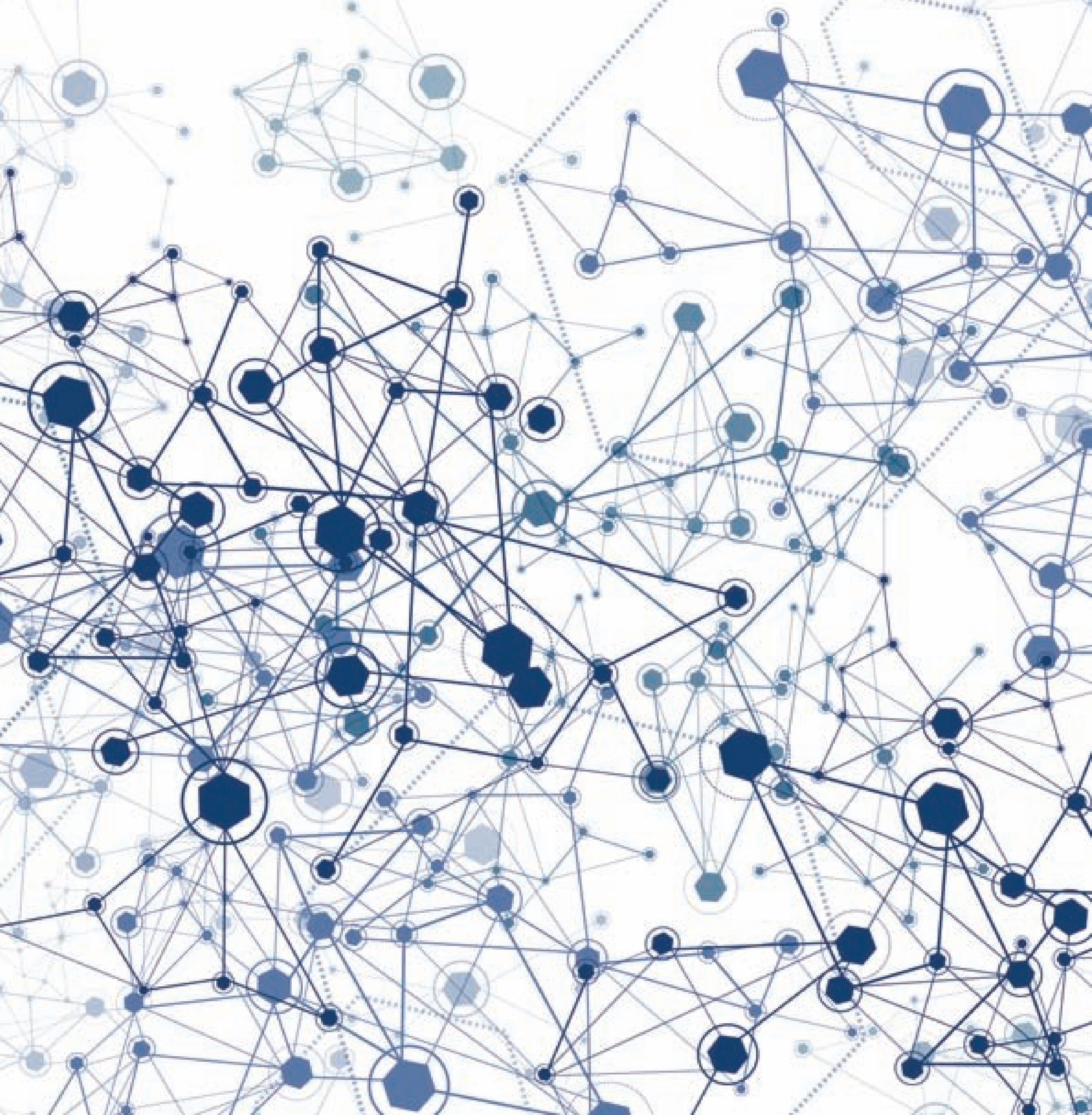
Policy and market design pose significant research challenges in this traditionally conservative sector. Challenges include: appropriate and sustainable business models for utilities and suppliers; the changing role of the user in future energy systems; investment in assets; long-term decision making under uncertainty; and market, governance and regulatory structures.

Some of the research challenges identified in component technologies include: the role of high voltage direct current (HVDC) in electricity networks; technical aspects of network control, offshore transmission components; technical aspects of integrating energy storage technologies; and power line communication technologies.

Recommendation: The research councils should ensure that a range of research challenges, spanning systems planning and operation, policy and market design and component technologies, are met.

7. Cross cutting conclusions

In the UK's networked energy innovation system, without central research institutes, different organisations must coordinate their activities effectively. The research councils need to work together to address research challenges lying at the boundaries of their spheres of interest. International cooperation can leverage the benefit of investments made in the UK.



The cross-cutting conclusions emerging from the workshop fall into three parts: a) those that relate to the way the research community, the research councils and others conduct their activities; b) those which relate to 'connections' - connections between UK energy innovation bodies, cross-sectoral connections (research, industry, policymakers etc.), international connections and public engagement; and c) specific issues relating to research training. The following three sections cover these areas.

7.1 Research conduct and support

Table 7 summarises which topics relating to research conduct and support received significant attention at each of our workshops. The remainder of the section considers these issues topic by topic in more detail.

7.1.1 Ways of Working

Cross-council working

The International Review Panel's on Energy recommended that ''a single, well defined, cross-Councils' energy research budget with coordinated deployment mechanisms be created to provide a common vision and strategy to the research community and to avoid conflicting priorities'. Although this has not occurred, the research councils are perceived to have made significant progress in addressing the spirit of this recommendation through shared funding for specific investments, e.g. UKERC and the EUED Centres. However, there was evidence from the workshops that opportunities were being missed and that some areas of research were 'falling through the cracks'.

Specific examples include bioenergy, where better co-ordination between BBSRC and EPSRC could improve coverage,[38] non-conventional fossil fuel extraction where NERC-EPSRC co-ordination is needed, and industrial energy demand where EPSRC and ESRC could collaborate.

Recommendation. Mechanisms for co-ordinating energy research across RCUK should be strengthened and greater use should be made of jointly commissioned research initiatives/consortia to respond further to the spirit of the International Review Panel's recommendation about a single well-defined energy research budget.

Collaboration between investments

The communities in a number of areas would value more linkages between related research investments. The nuclear community is well networked through the Nuclear Universities Consortium for Learning, Engagement and Research (NUCLEAR) and support for a research champion. The CCS community is also well served through the UK CCS Research Centre (UKCCSRC).

Recommendation. The research councils should consider establishing research networking/champion arrangements in areas of energy research to which particular priority is attached, where they have not done so already. Such arrangements have proved successful in areas such as nuclear and CCS.

Interdisciplinarity

Interdisciplinary research was mentioned at every workshop and is perceived to add value across the energy domain. Interdisciplinarity comes in two broad forms: that which draws together related disciplines lying within the sphere of a single Research Council; and that which draws together a wider range of disciplines supported by more than one Council. The greater challenge lies in promoting the latter more ambitious form of interdisciplinarity.

The observation that academic incentives operate against interdisciplinarity is persistent. Promotion criteria in universities and the value attached under the Research Excellence Framework (REF) to publication in single-discipline journals are both seen to inhibit interdisciplinarity. These are beyond the control of the research councils and are not discussed further.

The research councils have made considerable efforts to advance interdisciplinary research, notably through support for UKERC which has funded since 2004. The EUED Centres continue this pattern of support.

Recommendation. The RCUK Energy Programme should continue to support ambitious interdisciplinary research initiatives.

Various interdisciplinary architectures are needed. Although the RCUK Energy Programme is defined and dominated by the engineering and physical sciences, the role of the social sciences and economics is pervasive. This is particularly true in the energy demand area because energy-related consumption behaviour is influenced by a combination of social and technical factors and their interaction. This also applies to smart grids. The social sciences are needed to address attitudes to and the acceptability of supply side technologies. In the fossil fuel and CCS domain there need to be collaborations between the NERC and EPSRC communities. In the bioenergy field, interactions between the BBSRC and EPSRC communities are indispensable. The role of environmental science, social science and economics strategic workshop and our expert workshops identified specific disciplinary combinations, which could jointly address research problems in the energy domain.

The workshops and stakeholder interviews identified two further steps that could be taken to enhance interdisciplinarity. The first would involve drawing in disciplines, especially from the social

[38] Hybrid biological/thermochemical processing of biomass provides an example of a topic that 'falls between the cracks'

Table 7: Cross-cutting issues: Research conduct and support

	Industrial energy	Energy in the home and workplace	Transport energy	Fossil fuels and CCS	Electrochemical energy technologies and storage	Wind, wave and tide	Bioenergy	Nuclear Fission	Energy infrastructure	Strategic Workshops
Ways of working										
– Cross-council working	√		√	√		√	√			√
– Collaboration between investments	√			√	√		√	√		
– Interdisciplinarity	√	√	√	√	√	√	√		√	√
– Blue skies/ application								√		√
– Funding processes and requirements					√	√			√	√
Data										
– Collection and curation	√	√	√	√		√	√	√	√	√
– IP	√			√		√		√	√	√
– Legal/ethical		√						√	√	
– Establishing baselines		√		√						
Infrastructure and facilities										
– Experimental facilities	√			√	√			√		√
– Computational facilities	√				√	√		√		
– Field trials		√		√			√			
– Testing facilities			√	√	√	√		√	√	√
Long-term perspectives										
– Strategic planning					√		√	√	√	
– Project support				√	√		√	√	√	√
– Field trials/ experiments				√		√	√			√

sciences (e.g. management science, political science), that have played comparatively little role in the energy domain so far. Law, which falls within the remit of the Arts and Humanities Research Council (AHRC), has a pervasive role and also falls into this category.

Recommendation. The research councils, especially ESRC and potentially AHRC, should consider how disciplines which have not traditionally contributed to energy research could be engaged. Putting in place a process for mapping out potential contributions would be a good starting point.

There is also a perception, notwithstanding good progress in promoting interdisciplinarity, that research challenges in the RCUK Energy Programme continue to be framed by engineering and physical science perspectives. Alternative framings that can encompass a broad range of disciplines present a possible alternative. Illustrative examples include 'energy developments in the marine and coastal environment' (NERC) or 'the regulation of retail energy markets' (ESRC). Two factors operate against this approach: the natural tendency for the EPSRC-led RCUK Energy Programme to reflect the perspectives of the lead Council; and the relatively low visibility of energy in the strategies of other Councils.

Recommendation. EPSRC, in its leadership of the Energy Programme, should be receptive to ways of framing energy research challenges that derive from a wider range of disciplinary perspectives. At the same time, other Councils should clarify how energy is positioned within their Delivery Plans and actively promote alternative framings within RCUK.

Balancing science-inspired and application-inspired research

Basic 'blue-skies' research without any immediately identifiable benefits is risky but important in certain areas such as electrochemistry which has potential applications across a wide range including PV, battery storage and fuels cells. This type of research should continue to be funded as the UK stands as much chance as any other country of establishing global leadership in these areas.

There are different views regarding the appropriate balance between science-inspired and application-inspired research and the extent to which the research councils should engage in applied research verging on development and the piloting of technology. These different views generally reflect the nature of the energy applications on which the individuals concerned work. Working on applied research/development is not formally within the objects of the research councils under their Royal Charters and many in the research community argued that the research councils should not encroach on space in which organisations such as TSB and ETI have become established.

The balance between science- and application-inspired energy research varies across research councils, and even within an individual research council at different points in time. For instance, EPSRC support for marine renewables had an applied focus in the mid-2000s before ETI and TSB were created. Since then support has moved back from the applied research and development end of the spectrum. However this does vary between the research councils. For example, EPSRC's bioenergy research support (mainly on bioenergy conversion) is much more applied in nature than BBSRC's support for energy crop improvement and biological conversion.

Recommendation. The research councils should be more transparent about the blue skies/application orientation of their research support in specific areas and should consider adopting consistent approaches where different research councils are supporting related topics.

Funding processes and requirements

A number of observations regarding the current procedures through which the research councils commission energy research and suggestions were made for improvements. This section mainly flags discussion points for further consideration and offers only one recommendation.

There is a strong view among researchers in well-funded areas that productive research is fostered by achieving critical mass in thematic programmes, large scale consortium projects, research hubs and Centres. This community would argue that existing investments should be allowed to bid for additional funding to build up collaborative arrangements. Researchers operating in less well-funded areas and more fragmented communities have a different perspective and argue that it is difficult to break into well-established networks. There is a balance to be struck between realising the benefits of strong and stable collaborative arrangements and facilitating new entrants in emerging areas of research.

The SUPERGEN 'hub and challenge' model is well-regarded and has resulted in strong and effective collaborations. However, there is some concern that core SUPERGEN partners have insufficient influence over the research funded through challenge calls. There is also concern that too much time is spent on internal communication among the research teams and insufficient resources are allocated to communicating research impacts with potential users (e.g. policymakers). There should be opportunities for new partners to engage with SUPERGEN consortia during their lifetime.

The research community sees value in both responsive and targeted mode research funding, as well as public/private sector funding models. The latter could draw additional resources into academic energy research.

There are some concerns about the quality and fairness of the peer review process, especially in relation to interdisciplinary proposals. Academic reviewers sometimes appear to be marginally qualified. It was suggested that greater use could potentially be made of knowledgeable individuals from industry or other stakeholder groups.

There was a view that assessments of the quality of outputs from research supported by RCUK should be conducted with a view to informing future funding decisions. This goes in the opposite direction from recent EPSRC policy changes which have seen the ending of the requirement to submit a final report.

Funding mechanisms should be set out and communicated appropriately to ensure that researchers understand how to engage with them. However, researchers also have a responsibility to make ensure that they absorb thoroughly funding call specifications in order to make the best use of their own and others time.

Recommendation. The research councils should be more transparent about the way they prioritise research and choose funding mechanisms. There appears to be a logic behind most choices but the wider perception is that decisions emerge arbitrarily. There is a need to communicate better with the research communities about how decisions are framed by Strategic Plans and other considerations.

7.1.2 Data needs

There is a widespread understanding that high quality research which builds on what went before is underpinned by effective data collection, curation and sharing. Two themes emerged from our workshops, the first relating to perceived gaps in data collection and curation, the second to data curation and sharing.

The biggest data gaps were considered to be in the area of energy consumption, echoing generic conclusions reached by the IEA.[39] However, it was acknowledged that significant progress is being made in relation to household energy given the English House Condition Survey and the developing National Energy Efficiency Data-Framework (NEED).[40]

The lack of data on industrial/business energy consumption below the basic sectoral level and in terms of how energy is used in specific applications (high-temperature heat, motors etc.) is a particular gap. The flow of data from the private sector to academia could be increased by explicitly managing confidentiality and non-disclosure issues, for example via trusted intermediaries.

RCUK operates under general OECD guidance to the effect that there should be open access to the results of publicly funded research,[41] while taking account of the need to address confidentiality and intellectual property (IP) issues. All research councils require those that they fund to have data management policies in place.

Three research councils – ESRC, NERC and STFC – impose 'strong' data collection sharing requirements on those they fund (or in the case of STFC on those whose research they facilitate) and support data providers and/or management centres (Table 8). ESRC and NERC, by the nature of the science they support, are heavily engaged in observation and monitoring which generate data with manifest 'common good' characteristics. STFC's support for basic research can also be seen as for the 'common good'.

BBSRC and EPSRC devolve responsibility to researchers. The nature of much of the science supported by these research councils will, by its nature, generate commercialisable IP suggesting less need for strong policies to provide open access to data. However, data generated within several research areas in the BBSRC/EPSRC domains were identified as having 'common good' characteristics in our workshops:

- results of bioenergy crop trials;
- the physical and chemical characteristics of materials and heat transfer fluids;
- data on energy consumption in transport, buildings and industry; and
- data on the impact of policy interventions targeted at energy efficiency.

Recommendation. BBSRC and EPSRC should consider establishing stronger data sharing policies and identify or establish suitable repositories for data having manifest 'common good' characteristics. EPSRC should identify what types of data resulting from its support are priorities for curation and sharing.

In addition, the boundary between public data generated by NERC and the commercial data generated by its Centres and Surveys should be considered with a view to maximising open access.

7.1.3 Infrastructure and facilities

Energy R&D is underpinned by the physical infrastructure needed to support experiments, modelling, field trials and equipment testing.

Experimental facilities

Experimental facilities, including large centralised facilities operated by STFC (e.g. the Diamond Light source and the ISIS neutron source facility) and smaller facilities operated by individual universities, are required primarily for energy research underpinned by materials science. These facilities may also be used for work in the biological sciences. Materials science is applied across the energy domain particularly in relation to nuclear, fuel cells, PV and battery storage, but also across a wider range of combustion and renewable energy technologies.

[39] *IEA, Tracking Clean Energy Progress 2013: IEA Input to the Clean Energy Ministerial, http://www.iea.org/publications/TCEP_web.pdf*
[40] *https://www.gov.uk/government/organisations/department-of-energy-climate-change/series/national-energy-efficiency-data-need-framework*
[41] *OECD, Principles and Guidelines for Access to Research Data from Public Funding, Paris, 2007. http://www.oecd.org/sti/sci-tech/38500813.pdf*

Table 8: Research Council Data Policies

Research Council	Title	Main features
BBSRC	Data sharing policy	Implemented by integration into the processes of supporting and monitoring research (i.e. delivered by researchers). Sharing priorities are: data arising from high volume experimentation; low throughput data arising from long time series or cumulative approaches; models generated using systems approaches.
EPSRC	Policy framework on research data[44]	Expectations based. "Institutional and project specific data management policies and plans should be in accordance with relevant standards and community best practice and should exist for all data. Data with acknowledged long term value should be preserved and remain accessible and useable for future research"
ESRC	Research data policy[45]	Obligation–based. All ESRC-funded research projects, collecting or producing data, are required to develop and implement a data management plan to ensure that data are well managed during their life-cycle and are ready to be offered (to the relevant data services provider) for archiving and sharing when a project ends.
NERC	Data policy[46]	Obligation-based. All environmental data of long-term value generated through NERC-funded activities must be submitted to NERC Environmental Data Centres for long-term management and dissemination.
STFC	Scientific data policy[47]	Data management plans should exist for all data, including that generated through access to beam time at STFC supported facilities. It is expected that data should be managed through an institutional repository, e.g. as operated by a research organisation (such as STFC), a university, a laboratory or an independently managed subject specific database.

Energy is recognised as one of one of seven research challenge areas in the RCUK Strategic Framework for Capital Investment.[42]

There is a widespread view across the energy research community that STFC facilities are under-used in terms of the number of operating days available. This is an issue that goes beyond the energy domain. The aim in the STFC 2012-13 Operating Plan[48] is to run the ISIS facility for 120 days per year although the actual capacity is considerably higher. Researchers compete to gain access for their experiments on the basis of research quality and there is a risk that opportunities for high-quality experimentation are being passed up.

The underlying cause of the relatively low usage rates is that decisions about capital investment and operational spending are taken separately. Capital funding allocations, which include contributions from the Wellcome Trust, have been relatively generous. Operating budgets are now set jointly by the seven research councils through the Large Facilities Steering Group established in 2011.[49] Operating budgets are therefore subject, to a greater degree, to the disciplines imposed by the current economic austerity regime. Research councils other than STFC must trade off funding for facilities against direct research support for their communities. Even after budgets have been established, the availability of facilities can still be reduced as the result of changes in unit costs over which STFC has no control. Recent cost increases have been driven by electricity prices running ahead of inflation and policy costs such as those associated with the Carbon Reduction Commitment.[50] Ironically, both these costs are linked to Government energy and climate change policies.

[42] *RCUK, Investing for Growth Capital Infrastructure for the 21st Century: RCUK Strategic Framework for Capital Investment, 2012. http://www.rcuk.ac.uk/documents/publications/RCUKFrameworkforCapitalInvestment2012.pdf*
[43] *http://www.bbsrc.ac.uk/web/FILES/Policies/data-sharing-policy.pdf*
[44] *http://www.epsrc.ac.uk/about/standards/researchdata/Pages/policyframework.aspx*
[45] *http://www.esrc.ac.uk/_images/Research_Data_Policy_2010_tcm8-4595.pdf*
[46] *http://www.nerc.ac.uk/research/sites/data/policy2011.asp*
[47] *http://www.stfc.ac.uk/resources/pdf/stfc_scientific_data_policy.pdf*
[48] *STFC operating plan 2012-13, http://www.stfc.ac.uk/files/1375/1375_res_4.pdf*
[49] *ibid*
[50] *Science and Technology Facilities Council Annual Report and Accounts 2012-2013, http://www.stfc.ac.uk/files/2495/2495_res_1.pdf*

The resolution of these issues lies beyond the energy research domain. However, we make two recommendations addressed to RCUK more broadly. These should be viewed in the context of our earlier recommendation on pressing for energy research budget allocations that are more in line with the UK's ambitious energy and climate change goals.

Recommendation. In the longer term, decisions about capital investments and operating budgets should be more closely linked. This could be achieved in part by adopting a life-cycle perspective when capital decisions are made and making provisional commitments for subsequent operating spend. These could then be the subject of on-going review.

Recommendation. The research councils should keep under review, through their participation in the Large Facilities Steering Group, the level of support for the operating budget of facilities to ensure that capital-intensive infrastructure is exploited appropriately. STFC should consider how to balance continued support across all facilities against more intensive use of a more selective group of assets.

Computational facilities

Modelling and computational techniques play an ever larger role in energy and other domains. The ability to model at all scales down to the atomic level, especially when combined with experimental observation, is critical. The capacity to predict the behaviour of materials and components without testing them in practice can accelerate scientific development. Predictive models and modelling tools with time horizons of 10,000 years are needed to model geological systems associated with carbon storage.

The relevant communities would welcome support in the development of computational techniques and were perhaps not aware of services offered by STFC. User communities expressed more interest in fast, powerful and cheap computers that could be used locally than they did in the provision for central supercomputers. STFC could note these points in taking forward its delivery plans.

Field trials

The importance of supporting field trials and environmental monitoring emerged in several area of energy research:

- geological storage of carbon dioxide;
- unconventional fossil fuel extraction, including exploratory boreholes and the more effective use of existing boreholes;
- marine renewable technology trials;
- bioenergy crop production; and
- energy efficiency interventions.

In most of these areas, long-term monitoring (10 years or more) might be needed to gain an adequate understanding of outcomes. This relates to conclusions on long-term perspectives (Section 7.1.4).

Testing facilities

The need for testing facilities has been highlighted in a number of research areas. Progress is being made in this area, for example through the joint Leeds-Sheffield Low Carbon Combustion Centre established through capital support from DECC with operational costs borne through research council awards and commercial users. Other areas identified by workshop participants include:

- scientific, prototyping and large-scale testing facilities for scaling up electrochemical technologies from laboratory to commercial scale;
- facilities to test high-temperature materials;
- facilities for testing and demonstrating technical transport energy innovations (e.g. vehicle drivetrains) as well as social innovations (airport systems, traffic congestion techniques, business models, demand reduction interventions);
- in the infrastructure field, a national demand emulator, which could receive high temporal resolution of energy/power data from a spatially and demographically diverse range of housing, commercial and industrial loads; and
- links to the Low Carbon Network Fund which, with regulator approval, could provide support for test cities, regions or campuses allowing energy network components to be tested in real environments with real consumers.

7.1.4 Long-term perspectives

There is a natural preference among scientists for longer funding cycles coupled with a natural resistance among those who provide resources. During our consultations, we identified two ways in which scientific benefits, as opposed to comfort for individual scientists, could result from the adoption of longer term perspectives. These are: a) the adoption of research strategies that extend beyond the budgetary cycles associated with CSR periods; and b) field trials and experiments where the full consequences cannot be assessed within, say, a five year period.

Research Council strategic plans generally cover five-year periods. Yet, the UK has a 2050 GHG emission reduction target and both the UK and EU are considering detailed plans and targets for 2030. Some aspects of research council activities are planned on longer term timescales, e.g. large infrastructure facilities (see below) and longitudinal surveys (e.g. the British Household Panel Survey conducted by the UK Longitudinal

Studies Centre). The long-term strategic planning needed to support these types of investments could usefully be extended to other activities, notably field trials in the bioscience and monitoring associated with fossil fuel extraction or carbon storage.

Recommendation. In developing their Strategic Plans, the research councils should plan beyond the time horizons associated with budgetary cycles to enable long-term investments in infrastructure, surveys, trials and experiments to be exploited fully. Strategies should take account of long-term energy policy goals and associated uncertainties. Long-term plans should be flexible, should not be seen as establishing firm budgetary commitments and should be reviewed at regular intervals.

Recommendation. The research councils should be prepared to make selective longer-term research investments of 10 years or longer, subject to rigorous stage-gating procedures, where there is clear evidence that scientific benefits cannot be realised on a shorter timescale. Examples include field trials for crops, cohort studies in the social sciences and the evaluation of the impacts of policy interventions.

Some workshop participants argued that longer-term funding was also needed for interdisciplinary energy research in order to provide researchers from different disciplines with the necessary time and support to develop mutual understanding and working relationships.

7.2 Making connections

A major theme running through the workshops and consultations has been the need for networking activities and connections between different parts of the energy innovation system. This section covers four types of connections: between different parts of the energy research domain; between the research councils and other energy innovation bodies; international working; and public engagement. The final sub-section broadens the focus to examine the wider picture of energy research alongside government policy. Table 9 summarises the key outputs of this section.

7.2.1 Linking research areas

The Energy R&D Wheel (Figure 1) underlines the interconnectedness of the energy research landscape and makes it clear that many energy research challenges are linked or draw on similar scientific and engineering skills. The evidence gathered during our workshops has led to the identification of specific areas where research funders and the research community need to be alert to related challenges and problems.

These are set out in matrix form in Table 10 with the topics of our workshops defining the axes. Unsurprisingly, energy infrastructure is the most connected topic as this integrates individual technologies and components as well as the practices of energy suppliers and users. Fossil fuels and CCS have connections with nuclear and renewable energy (geothermal) via the geological sciences. Bioenergy is also strongly connected because of applications for stationary heat and power, transport biofuels and combustion science. Electric and hybrid vehicles and transport biofuels as alternative to conventional internal combustion engines means that the transport energy area impinges on several other areas.

Electric and hybrid vehicles and transport biofuels as alternative to conventional internal combustion engines means that the transport energy area impinges on several other areas.

Recommendation. The research councils should note relevant connections between different research areas when planning new research investments, particularly in relation to the cross-cutting research themes of materials science, socio-economic issues and environmental science.

Table 10 also sets out three cross-cutting disciplinary areas and identifies the research areas where they are *principally* relevant. Materials science is of critical importance in relation to industrial energy use, electrochemical energy technologies (including PV) and nuclear. It is also relevant to other areas including fossil fuels, CCS and other renewables. Socio-economic issues had the highest profile at workshops with respect to human behaviour on the demand side, especially energy in the home and workplace and transport energy, and in relation to energy infrastructure (smart grid). Energy consumption behaviour and the way people interact with technology were the key emerging themes. However, there are also important research questions concerning public acceptability and attitudes to energy supply technologies. Environmental science has a cross-cutting role to play, especially in relation to supply side technologies and infrastructure, where there is a strong interaction with social science agendas.

Table 9: Cross-cutting issues: Connections and the bigger picture

	Industrial energy	Energy in the home and workplace	Transport energy	Fossil fuels and CCS	Electrochemical energy technologies and storage	Wind, wave and tide	Bioenergy	Nuclear Fission	Energy infrastructure	Strategic Workshops
Linkages										
– Other innovation support bodies	√	√	√	√	√	√	√	√	√	√
– Policymaking	√	√	√	√	√		√	√	√	
– Industry	√	√	√	√	√	√	√	√	√	√
– Knowledge exchange		√		√	√	√	√			√
International working										
– EU		√	√		√	√		√		√
– Wider international			√					√		√
Public engagement				√	√					√
The bigger picture										
– Policy clarity	√	√		√			√	√		√
– Horizon scanning							√	√		√
– Strategic road-mapping	√	√		√	√			√		

Table 10: Linking research challenges across the energy domain

	Industrial energy	**Energy in the home and workplace**	**Transport energy**	**Fossil fuels and CCS**	**Electrochemical energy technologies and storage**	**Wind, wave and tide**	**Bioenergy**	**Nuclear Fission**	**Energy infrastructure**
Energy in the home and workplace	Generic technologies (motors etc); decision-making								
Transport energy		Consumption behaviour							
Fossil fuels and CCS	CCS; fossil fuel use		Refining, oil and gas storage						
Electrochemical technologies/ storage		Stationary fuel cell devices	Fuel cells and batteries, hydrogen storage						
Wind, wave and tide									
Bioenergy	Biomass heat and power		Transport biofuels	Conversion and combustion; biomass heat and power					
Nuclear Fission				Uranium/ thorium extraction; nuclear waste storage					
Energy infrastructure	Load balancing; heat networks; hydrogen networks	Demand side participation, distributed generation	Electricity vehicles, charging infrastructure		Integration of storage and other devices (e.g. fuel cells, PV)	Renewable integration, offshore transmission			
Other	District heating	Heat pumps	Hydrogen production	Geothermal energy					
Materials science	√				√			√	
Socio-economic	√	√	√						√
Environmental				√		√	√	√	√

7.2.2 The research councils and the wider energy innovation landscape

Wider innovation support

There is a widespread view that there needs to be a more joined-up approach across the innovation landscape with the research councils, TSB, ETI, industry, DECC and other government departments acting in concert. The establishment of LCICG as a coordinating mechanism is welcomed and high expectations about what it can deliver may need to be managed.

Active collaboration is emerging but this could be enhanced through a combination of approaches including jointly-funded research projects and secondment schemes, both into and from academia, for individuals at the early, mid and advanced stages of their careers. There is interest in Catapult Centres as platforms for collaboration between academia and industry. Engaging industry will prove important to ensure that industry takes ownership of innovations emerging from RCUK funded research.

Recommendation. The research councils and other bodies should build on progress in coordinating energy RD&D across the innovation landscape by contributing to the effective operation of the LCICG and engaging in active collaboration through, for example, joint funding calls encompassing activity along the innovation chain.

Given that energy infrastructure RD&D stimulated through the RIIO regulatory framework overseen by Ofgem is having and will continue to have a significant impact on the research landscape, including areas where the research councils have lead responsibility, there is strong case for Ofgem becoming more centrally engaged in coordination processes.

Recommendation. Ofgem's role in LCICG should be upgraded from associate to full membership given its role in stimulating energy network RD&D which is having a significant impact on the research landscape. This would ensure better integration and facilitate an appropriate allocation of energy RD&D resources.

Policy making

There is a perceived disconnect between the UK research community and those in the policy world. Links with DECC and BIS are priorities to ensure that: a) important innovations and research findings and innovations are taken into account by policymakers; and b) that the establishment of research priorities benefit from guidance about policy needs. Chief Scientific Advisers (CSAs) have a key role to play in bridging the research and policy worlds.

Resolving policy and research timeframes

The policy landscape is moving more quickly than the research landscape meaning that valuable evidence generated by academia may not be ready in time to inform policy. Fast tracking certain funding calls may help this. There is a similar issue between power engineering and ICT communities, which operate on different timescales. ICT is a fast-moving sector, with innovations occurring on a yearly timescale. In comparison, power engineering is a more conservative sector with a slower pace of innovation and deployment.

Industry links

In developing their research strategies for industry engagement, the research councils need to take account of the fact that industry works mainly through incremental improvements. Among the most valuable help that industry could receive is in identifying and accessing the academic skills base.

Better and more systematic links between industry and academia would help to improve the handling of IP issues in funding bids.

Knowledge exchange

Knowledge exchange mechanisms to facilitate industry-academia linkages are seen as important. The activities of the energy-related Knowledge Transfer Networks (KTNs) are valued.

There is a need for interaction between trade associations, major companies and academics. One possible mechanism is a Memorandum of Understanding (MoU) between EPSRC and relevant trade associations. BIS has a potentially useful role in facilitating this.

7.2.3 International working

The UK energy research community is actively engaged in international collaboration and is aware of the opportunity to leverage UK domestic efforts and avoid duplication. At the same time, the community is conscious of barriers to engagement associated with the amount of effort required upfront to develop international projects and the practical issues of undertaking research with multiple partners.

UK researchers have performed relatively well in terms of participation in EU Framework Programmes, though those is less the case for industry. This is in spite of specific barriers such as the mismatches between institutional structures and funding arrangements in the UK and those that predominate in continental European countries.

The structure of EERA, for example, is based on the premise that EU Member States have large central research organisations that can lead national participation. The research community welcomes the initiative that the research councils have taken in positioning UKERC to lead UK engagement and facilitate involvement in the EERA Joint Programmes by the UK's more dispersed research community. Building on efforts to date will help the UK access the expanded energy research funding available through Horizon 2020.

The IEA and its Implementing Agreements (IAs) provide another avenue for coordinating international energy research activity.

UK researchers participate in these in an ad hoc manner. DECC has lead responsibility for UK engagement with both the IEA and EU and has very limited resources for coordinating such engagement. A greater level of effort could help identify and reduce duplication of effort between the UK and international programmes and enhance the quality as well as the financial value of UK collaboration. This would require cooperation between the various bodies responsible for energy RD&D, e.g. the research councils, DECC, TSB and ETI, and the LCICG appears to be the natural focus for such efforts, perhaps through the establishment of focused sub-group.

Recommendation. The UK should exert greater influence over the development of EU programmes and attempt more co-ordination of programme involvement. The research councils should continue to support UKERC in leading the engagement of UK researchers in EERA and Horizon 2020. LCICG could act as the focus for UK engagement with the EU and IEA more broadly. Effective co-ordination would need more resource than are currently being allocated.

The research community endorses the 'best with best' principle when the research councils develop international collaboration arrangements. The community welcomes the MoUs signed with, and the RCUK presence in, key countries such as China, India and the United States. However, in some areas of energy research, countries other than those currently identified as priorities may have research leadership. In the energy infrastructure area, South Korean progress on smart grids was highlighted. Although RCUK cannot have a physical presence in a large number of countries, the FCO/BIS Science and Innovation Network (SIN) could facilitate collaboration.

Recommendation. The 'best with best' principle should be implemented rigorously when developing international collaboration. International co-operation efforts could be selectively extended beyond the current group of priority countries on a topic by topic basis.

7.2.4 Public engagement

Public engagement is an objective for each of the research councils under their Royal Charters. The topic of public engagement emerged at several of the expert workshop we convened (*Fossil Fuels and CCS; Energy in the Home and Workplace*). Participants generally encouraged engagement and believed this should be a two-way process rather than one-way communication. However, few clearly articulated actions emerged to take forward the public engagement agenda. Our final stakeholder synthesis workshop offered some useful insights.

Research agendas often develop over long time periods, longer than the life cycle of an issue that a member of the public may be interested or involved in. Many of the subjects researchers wish to engage the public with may have little actual bearing on everyday lives or be of little direct interest. It would be more effective to integrate energy issues into a public engagement agenda defined by wider issues that the public is actually concerned about, rather than focusing strictly on energy.

The research councils need to be clear about what role stakeholders can realistically play in setting research agendas lest expectations are created that cannot be realised in practice. Energy research may be associated with 'hard truths', such as impending threats to energy security and affordability. It is possible that the public may initially be unreceptive to energy research findings.

Recommendation. Research councils should establish a framework for public engagement that starts from the top and does not simply pass responsibility down to individual programmes and projects. Consultation and engagement over the development of Strategic Plans would be a good starting point. Such engagement should explicitly address the degree to which stakeholder views may or may not be reflected in the development of research agenda so that realistic expectations are established. A high level framework could guide engagement processes at the programme and project level.

7.2.5 The wider picture

Despite considerable policy efforts in recent years (the Carbon Plan, Electricity Market Reform, Green Deal), the energy research community does not believe that a clear and convincing vision of the UK's future energy system has been established. If such a vision existed, it could inform the development of strategic roadmaps that point clearly towards research challenges relevant to future energy needs. Clarity about the direction of energy policy and a consistent vision of the future coupled with a sustained long-term funding structure would also encourage younger researchers into the field.

However, the research community's expectation about policy clarity may be unrealistic. This underlines the need for a portfolio approach to investments in energy research whose pay-off will be in the longer term.

7.3 Training

General

Although UK doctoral and masters programmes are world leading, it is believed that there is a shortfall of science and engineering graduates relative to the UK needs in the energy field. The appropriate balance between research and training has not so far been demonstrated.

Recommendation. Data on doctoral and masters programmes, including numbers and types of students and specific strategic shortfalls, should be gathered in order to identify the current state of the area.

PhD funding models

Across all areas, the research community has expressed regret that EPSRC decided to focus all of its support for PhD training on Centres for Doctoral Training (CDTs). There have been acknowledged problems with project-based PhD support (isolated students, lack of mentoring, use as inexpensive sources of research assistance) but it is believed that these issues could be addressed by imposing conditions on project-based PhD studentships given that they can offer some advantages including experience of interdisciplinary working, team-working and extensive mentoring.

Funding models that incorporate industrial support, such as CASE studentships and Engineering Doctorates, were particularly welcomed by some members of the community. This was due to the opportunities they offered to PhD students to experience working in both academic and industrial environments, in turn presenting them with a balanced portfolio of skills and experiences.

Recommendation. EPSRC funding models for PhD training could blend different approaches - CDTs, project-based, EngDs - in a way that enables prospective students to choose the training experience that best supports their longer-term career aspirations. Any new model should include safeguards to embed students within a research community and prevent them becoming isolated. Other research councils could learn from EPSRC's experience in this respect.

Transferable skills

There is persistent uncertainty about the availability of long-term career paths for doctoral student and post-doctoral research associates, as noted by the International Review Panel in 2010. Given the great uncertainties around the future path that the UK energy system might take, PhD training should foster the development of transferrable skills that could be applied in other parts of the energy domain or more widely. A balance between the acquisition of deep skills and wider transferrable skills is needed. Some have argued that focusing on CDTs on specific technology applications is developing skills in an unduly narrow way.

Recommendation. The transferability of research skills should be considered so that people enjoy good employment prospects even if specific energy technologies do not achieve widespread deployment. CDTs might, for example, be structured round clusters of technologies that require similar skill-sets rather than individual technologies.

Understanding of the wider context

Training in the energy field should give students a sense of the bigger picture into which their research fits and of the content and value of other disciplines. Specifically, PhD students with pure science/engineering degrees would benefit from additional training to improve their general awareness of the wider energy context. New knowledge arising from research council investments could also be incorporated into this and wider engineering education.

Training in the energy field should give students a sense of the bigger picture into which their research fits and of the content and value of other disciplines. Specifically, PhD students with pure science/engineering degrees would benefit from additional training to improve their general awareness of the wider energy context.

Industrial and policy links

Given the applied nature of much of the research in this field, secondments across sectors – academia, industry, policy – would be particularly valuable. However, experience of secondments in some sectors (e.g. nuclear fission) has not been uniformly positive. Industrially supported Engineering Doctorates could also help provide students with greater experience of more applied energy research.

Professional development and career progression.

If the UK's research capacity in this area is to be expanded, more mid-career researchers capable of supervising masters and doctoral students will be needed. Currently there are many high quality PhD applicants but fewer qualified postdocs. Researchers need support at the early stages of their careers.

Masters training

There is some support, notably from industry in this sector, for the research councils supporting masters level training.

If the UK's research capacity in this area is to be expanded, more mid-career researchers capable of supervising masters and doctoral students will be needed.

8. Conclusions

Strong relationships between the research councils, the research communities they support and wider stakeholders will best be served by transparent processes for research and training support. Effective consultation and communication are needed to build trust and support for energy research activities.

The consultations, workshops and documentary analysis that support this report have provided a comprehensive overview of energy research activities supported by the research councils and the connections between these activities and other energy innovation bodies, industry and policymaking.

The report represents part of the response to the recommendation of the 2010 International Review Panel that "a fully integrated 'roadmap' for UK research targets be completed and maintained to allow all to know and understand what is considered essential to meet society's needs".

This report's findings are in five areas:

- It has gathered evidence strongly endorsing the portfolio approach to energy research taken by the RCUK Energy Programme.
- It has identified the roles that broad areas of energy research, e.g. in energy infrastructure or fossil fuels, can play in meeting economic and social needs, their contributions to energy and climate change policy, and the competitiveness and growth agenda.
- It has identified high-level research priorities within each of these areas and, in the supporting documents,[51] more specific research challenges and questions.
- It has identified issues regarding the way research is conducted and supported, and the way connections are made across the energy innovation domain, offering recommendations for improving these.
- It has generated suggestions for the support of training, primarily at the doctoral level but also at the masters level, as well as recommendations to promote career development.

However, this report represents only part of an on-going iterative process. Within the time and resources available it has not been possible to make recommendations about how specific calls for proposals might be structured and targeted. That would require further work and consultation with the respective communities. Detailed information on financial support and levels of activities (e.g. number of PhDs) in specific areas is lacking. Whilst certain areas of energy research such as nuclear and CCS, are well-networked and active in mapping their activities and formulating forward research agendas, others are less so. These communities are therefore likely to require further prompting and support from the research councils in this regard. The recommendations we have made have resource implications. We would argue that modest resources invested in co-ordination activities, in the research councils, other innovation bodies and government departments, would leverage better innovation outcomes and would represent good value-for-money.

The report has generated a long list of recommendations. Like the International Review Panel, we have found it hard to ignore the wider context in which the research councils operate. Therefore, whilst some of our recommendations are aimed at the research councils specifically, others are relevant to the UK's energy innovation bodies more broadly. Consequently, our recommendations are categorised according to their focus: the wider energy innovation system; research councils more broadly; the RCUK Energy Programme; and topic-specific research questions.

From the recommendations, three issues stand out:

The level of financial support for energy innovation. This is well below the level commensurate with the UK's ambitious energy and climate change targets and would need to be raised considerably to bring it in line with our international peers.

Cross-council and interdisciplinary working. Although considerable progress has been made, much work remains to be done to establish suitable collaborative arrangements that satisfy the spirit of the International Review Panel's recommendation for "a single, well defined, cross-Councils' energy research budget with coordinated deployment mechanisms".

Communication and transparency. There is an-going need to communicate the relationship between the research councils' Royal Charter objectives, their Strategic and Delivery Plans, and the specific choices that are made in supporting research and training activities. The logic behind the research councils' decision- making is not always understood by the research community.

Recommendation. The research councils should be more transparent about the way they prioritise research and select funding mechanisms. The logic behind many choices is not explained and the wider perception is that decisions emerge arbitrarily. There is a need to communicate better with the research communities about how decisions are framed by Strategic Plans and wider considerations.

[51] *See http://www3.imperial.ac.uk/rcukenergystrategy/prospectus/documents for access to supporting documents.*

ANNEX A: The objects of the research councils under their Royal Charters

Common objective	Council	Additional/variant	Focus
High-quality basic, strategic and applied research			
To promote and support, by any means, high-quality basic, strategic and applied research and related post-graduate training	BBSRC		relating to the understanding and exploitation of biological systems
	EPSRC		in engineering and the physical sciences
	ESRC		in the social sciences
	NERC	survey, long-term environmental observation and monitoring (additional)	In environmental and related sciences including: terrestrial, marine and freshwater biology and Earth, atmospheric, hydrological, oceanographic and polar sciences; and in Earth observation and the Earth's system.
	STFC		in astronomy, particle physics, space science and nuclear physics and research in any other field which makes use of scientific facilities where access is provided, arranged or otherwise made available by the Council, having regard to the objects of the other research councils.
Knowledge, technology and training			
To advance knowledge and technology, and provide trained scientists and engineers, which meet the needs of users and beneficiaries ……. thereby contributing to the economic competitiveness of the UK and the quality of life.	BBSRC		User and beneficiaries include the agriculture, bioprocessing, chemicals, food, healthcare, pharmaceutical and other bio-technology related industries
	EPSRC	includes the promotion and support of the exploitation of research outcomes	User and beneficiaries include the chemical, communications, construction, electrical, electronic, energy, engineering, information technology, pharmaceutical, process and other industries
	ESRC	also contributing to the effectiveness of public services and policy	
	NERC	includes the promotion and support of the exploitation of research outcomes; also contributing to the effectiveness of public services and policy	User and beneficiaries include the agricultural, construction, Earth observation, energy, environmental services, fishing, forestry, hydrocarbons, financial services, minerals, process, remote-sensing, water and other industries.
	STFC	Different words, same essence	

ANNEX A (continued) : The objects of the research councils under their Royal Charters

Common objective	Council	Additional/variant	Focus
Facilities			
To promote and support high-quality scientific and engineering research by developing and providing, by any means, facilities and technical expertise in support of basic, strategic and applied research programmes funded by persons established in the UK and elsewhere	STFC		
Advice, dissemination of knowledge and public understanding			
Model 1: to provide advice, disseminate knowledge, and promote public understanding	BBSRC		in the fields of biotechnology and the biological sciences.
	ESRC		of the social sciences.
Model 2: in relation to the activities as engaged in by the Council and in such manner as the Council may see fit: to generate public awareness; to communicate research outcomes; to encourage public engagement and dialogue; to disseminate knowledge; and to provide advice.	EPSRC		
	NERC		
	STFC		

Note: *Royal Charters were issued: BBSRC (1993); ESRC (1993); NERC (1993); EPSRC (2003); STFC (2007)*

ANNEX B:
Follow-up to the high-level conclusions of the International Review Panel on Energy

Recommendation	Follow-Up
A fully integrated "roadmap" for UK research targets be completed and maintained to allow all to know and understand what is considered essential to meet society's needs.	The *Energy Research and Training Prospectus* responds to this recommendation. The Prospectus specifically addresses social, economic and environmental needs as well as public engagement. The Low Carbon Innovation Coordination Group (LCICG) is taking this agenda forwards across the wider energy innovation domain.
A single, well defined, cross-Councils' energy research budget with coordinated deployment mechanisms be created to provide a common vision and strategy to the research community and to avoid conflicting priorities. Such a coordinated approach should also enhance the linking of RCUK funds to wider resources.	The *Prospectus* supports this recommendation which also has wide support in the research community. The research councils have responded to this recommendation without having gone as far as creating a single well-defined energy research budget.
The allocation process for strategic programmes needs to be more transparent and anchored to clear plans to ensure better research community involvement and acceptance as well as a better targeting of deliverables. At the same time, the current level of support for open ended programmes is seen as appropriate.	The Prospectus develops further the theme of transparency and makes further procedural recommendations in this area.
Many application areas are best served by interdisciplinary R&D. There needs to be increased efforts to identify opportunities, provide funding and then promote, recognise and reward interdisciplinary R&D.	The *Prospectus* reflects strong research community support for this proposal but also identifies the continued existence of barriers and slow progress in overcoming them.
Postdoctoral graduates are a critical element of the UK's human capital. To ensure long-term engagement in the UK, there needs to be more attention and resources directed to career paths both in industry and academia. It should be recognised that international careers and experiences are beneficial.	This theme has been further developed in the *Prospectus*, notably the need to encourage the development of transferrable skills in light of inherent uncertainties about energy sector development.
Meeting climate change targets of necessity requires reduction in energy demand across the board. R&D on demand reduction needs a higher profile in the R&D portfolio and may warrant a dedicated programme.	Five *Energy End Use Demand* (EUED) Centres have been established. Three of the nine Prospectus energy areas are on the demand side and a fourth (infrastructure) bridges demand and supply.

The *Prospectus* reflects strong research community support for this proposal but also identifies the continued existence of barriers and slow progress in overcoming them.

Annex C: List of workshops held

Strategy Workshop 1: Energy Strategies and Energy Research Needs	London	24 October 2012
Strategy Workshop 2: The Role of Social Science, Environmental Science and Economics	London	13 November 2012
Expert Workshop 1: Fossil Fuels and CCS	Edinburgh	8-9 January 2013
Expert Workshop 2: Energy in the Home and Workplace	Warwick	5-6 February 2013
Strategy Workshop 3: Research Councils and the Energy Funding Landscape	London	20 February 2013
Expert Workshop 3: Energy Infrastructure	Birmingham	17-18 April 2013
Expert Workshop 4: Bioenergy	Rothamsted	14-15 May 2013
Expert Workshop 5: Transport Energy	Coventry	11-12 June 2013
Expert Workshop 6: Electrochemical Energy Technologies	Oxford	26-27 June 2013
Strategy Workshop 4: Synthesis Workshop	London	15 July 2013
Light Touch Workshop 1: Industrial Energy	London	17 July 2013
Light Touch Workshop 2: Wind, Wave and Tidal Energy	London	25 September 2013

Annex D: Energy Strategy Fellowship Advisory Group

Peter Taylor (Chair)	University of Leeds
Julian Allwood	University of Cambridge
Jo Coleman	Energy Technologies Institute
Jane Dennett-Thorpe	DECC
David Infield	University of Strathclyde
Ron Loveland	Welsh Assembly Government
Sara Parkin	Forum for the Future
Nick Pidgeon	University of Cardiff
Jean-Benoit Ritz	EDF
Robert Slade	University of Surrey
Steve Sorrell	University of Sussex
Gail Taylor	University of Southampton
Jacqui Williams	EPSRC

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