Research Councils UK Energy Programme Strategy Fellowship

ENERGY RESEARCH AND TRAINING PROSPECTUS: REPORT NO 5

Fossil Fuels and Carbon Capture and Storage

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Research Councils Energy Programme

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

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

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

Energy Strategy Fellowship

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

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

One of the main inputs to the Prospectus has been a series of four high-level strategic workshops and six in-depth expert workshops which took place between October 2012 and July 2013. The main report, *Investing in a brighter energy future: energy research and training prospectus*, was published in November 2013. This is one of nine topic-specific documents supporting the main report. All reports can be downloaded from: www3.imperial.ac.uk/rcukenergystrategy/prospectus/documents/reports. This first version of the Prospectus will be reviewed and updated on an annual cycle during the lifetime of the Fellowship, which ends in 2017.

This report is the product of work conducted independently under EPSRC Grant EP/K00154X/1, Research Councils UK Energy Programme: Energy Strategy Fellowship. The draft report was reviewed by Sam Holloway of BGS, Haroon Kheshgi of ExxonMobil and Fabian Wagner of IIASA. While the report draws on extensive consultations, the views expressed are those of the Fellowship team alone.

Contents

Executive Summary

This report primarily covers research in the fields of fossil fuel extraction and use and carbon capture and storage (CCS). Geothermal energy was also covered given that this area requires similar skills. The most important input to the report has been a two-day residential expert workshop involving 26 attendees. Most were from the communities supported by the Natural Environment Research Council (NERC) and the Engineering and Physical Sciences Research Council (EPSRC). In addition, a number of attendees came from private sector and government organisations.

The dominant role of fossils fuels in the UK and the global energy systems is likely to continue for some time. 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 the degree to which strong climate change policies are implemented. For example, fossil fuel use would need to contract significantly if the UN Framework Convention on Climate Change (UNFCCC) climate objective of keeping global temperature increases below 2°C above pre-industrial levels were to be realised. CCS technology can help to reconcile climate policy goals and the use of fossil fuels. The research councils should hedge against these uncertainties by investing both in research that will improve the extraction and use of fossil fuels and in research relating to CCS. The skills acquired though doctoral training either domain are likely to have wider application.

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. The UK's competences in relation to coal extraction and exploitation are believed to be weaker, as are those in relation to coal bed methane (CBM), underground coal gasification (UGC) and geothermal energy. 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).

Research priorities covered by this report fall into three broad categories: sub-surface energy extraction; 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 resources of conventional coal, oil and gas; 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 (biomass energy with CCS); membranes, adsorbents and capture looping; air capture; and biomimetic carbon dioxide (CO_2) capture. The research community can also contribute to more near-term challenges including: capture retrofit on 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, notably the issue of liability and risk sharing between government and operators. Understanding the impacts of novel methods of energy extraction and CCS on the environment and ecosystem services is another priority area.

Many of these research challenges are not unique to the UK. Given the large scale of the R&D activities required in the fossil fuel and CCS domain, challenges that are common across countries may best be pursued internationally rather than through the UK acting alone. Other research challenges, such as those relating to resource characterisation and regulatory design, are UK-specific. Much of the R&D in the fossil fuel area is of an applied nature relating to the improvement of mature technologies and techniques. Such R&D is generally conducted by private companies. The main role of public sector R&D is to develop generic knowledge regarding resources and their characterisation, develop and advance pre-commercial technologies, respond to basic science and engineering problems suggested by technology demonstration and deployment and support the regulation of the sector.

Further development of high-level research challenges is needed to establish concrete research plans. Given the deep uncertainties about energy futures, the development of portfolios of research activity that can be adapted in the light of changing priorities and new knowledge would be advisable.

There are several ways in which research outcomes could be enhanced in this area: achieving critical mass through large-scale consortia and programmes; and better cross-Council working, including jointly funded projects, particularly those linking NERC and ESPRC. The need to link engineers and geologists is particularly important.

As in some other areas of energy research, there is an arguable scientific case for longer-term funding support as investments in field trials and pilot studies may take some years to yield their full scientific benefit. Linking research to field trials would be particularly beneficial. The fossil and CCS community also have concerns about data-sharing and access to experimental, testing and computational facilities.

The role of the research councils in providing qualified scientists and engineers is much valued, notably in industry where much of the relevant R&D takes place. As in all areas of energy research, there is opposition to the exclusive use of the Centre for Doctoral Training (CDT) model in delivering PhD training. While the CDT model is a good one, it is believed that it has led to a big gap in the supply of trained people. A system where CDTs are complemented by project and discipline-based studentships would be more appropriate. Given uncertainties about the long-term future in this sector, PhD training should be designed so that the skills attained can remain relevant even if the industry changes radically. A balance between the acquisition of deep skills and wider transferrable skills is needed. There is some support, notably from industry, for the research councils to fund Masters level training.

There is a widespread view that the research councils, Technology Strategy Board (TSB), the Energy Technologies Institute (ETI), the Department of Energy and Climate Change (DECC), the Department of Food, Environment and Rural Affairs (Defra) and industry need to act in concert, clearly establishing who funds what. Joint action should focus on the appropriate tasks for public sector R&D, notably generating generic knowledge regarding resources and their characterisation and developing and advancing pre-commercial technologies. Common agreed frameworks combined with flexible and adaptable research portfolios are needed to support technological development. The Low Carbon Innovation Coordination Group (LCICG) could help to facilitate in this area.

In this field, understanding public perceptions and the degree of acceptance of new technologies is essential. It is believed that the research councils could do more, though only a limited number of practical ideas (e.g. reach-out events in schools) has emerged.

In this, as in most other area of energy research, the community believes that clarity about the direction of energy policy and a consistent vision of the future coupled with a sustained long-term funding structure would greatly help with research planning and encouraging younger researchers into the field. However, the community needs to respond to continuing uncertainty by developing and pursuing flexible research portfolios.

Acronyms

2DS	two degree scenario
BBSRC	Biotechnology and Biological Sciences Research Council
BCURA	British Coal Utilisation Research Association
BECCS	biomass energy with CCS
BF2RA	Biomass and Fossil Fuel Research Alliance
BGS	British Geological Survey
CBM	coal bed methane
CCC	Committee on Climate Change
CCGT	Combined Cycle Gas Turbines
CCS	carbon capture and storage
CDT	Centre for Doctoral Training
CHP	combined heat and power
CO_2	carbon dioxide
CSLF	Carbon Sequestration Leadership Forum
DECC	Department of Energy and Climate Change
Defra	Department of the Environment, Food and Rural Affairs
DOE	Department of Energy (US)
ECSC	European Coal and Steel Community
EIA	Energy Information Administration (US DOE)
EII	European Industrial Initiative
EPA	Environmental Protection Agency (US)
EJ	exajoiules
EPSRC	Engineering and Physical Sciences Research Council
ESME	Energy Systems Modelling Environment (an energy system model)
ETI	Energy Technologies Institute
GHG	greenhouse gases
IEA	International Energy Agency
IP	intellectual property
LCICG	Low Carbon Innovation Coordination Group
LNG	liquefied natural gas
M&R	mitigation and remediation
MARKAL	MARKet ALlocation (an energy system model)
MMV	measuring, monitoring and verification
NCIL	no clear international lead
NERC	Natural Environment Research Council
NETL	National Energy Technology Laboratory (US)
PC	pulverised coal
PJ	petajoules
R&D	research and development
RAMO	reliability, availability, maintainability and operability

RCUK	Research Councils UK
RD&D	research, development and demonstration
REF	Research Excellence Framework
RFCS	Research Fund for Coal and Steel
SET	Strategic Energy Technology (EU R&D plan)
STFC	Science and Technology Research Council
TINA	technology innovation needs assessment
TRL	technology readiness level
TSB	Technology Strategy Board
UCG	underground coal gasification
UKCCSC	UK Carbon Capture and Storage Consortium
UKCCSRC	UK Carbon Capture and Storage Research Centre
UKERC	UK Energy Research Centre
UNFCCC	UN Framework Convention on Climate Change
USGS	US Geological Survey

1. Introduction

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

The most important input to this report has been a two-day, facilitated expert workshop held at Pollock Halls, Edinburgh on 8-9 January 2013. There were 26 attendees at the workshop (excluding the Fellowship and facilitation team), most of whom were academics and researchers falling within the communities supported by the Natural Environment Research Council (NERC) and the Engineering and Physical Sciences Research Council (EPSRC). In addition, a number of attendees were from private sector and government organisations. A full report of the workshop has previously been published as a working paper.[1] The working paper was the document of record and has acted as an intermediate step in the production of this report which focuses on key messages and recommendations. The workshop also drew on the outcomes of a series of 'strategy' workshops which addressed: **energy strategies and energy research needs; the role of the environmental and social sciences**; and **the research councils and the energy innovation landscape**. Reports of these workshops are also available on the Fellowship website.[2]

The conclusions respond to a recommendation of the 2010 International Panel for the RCUK Review of Energy[3] that the research supported by the research councils should be more aligned with the UK's long-term energy policy goals. The key criteria used in developing this report have been the three pillars of energy policy – environment, affordability and security – coupled with potential contributions to UK growth and competitiveness.

The Fellowship team is using the EU/International Energy Agency (IEA) energy research and development (R&D) nomenclature[4] to map out the energy research landscape. This report primarily covers Area II, **Fossil Fuels: Oil, Gas and Coal**. The research challenges and needs identified in Sections 5 and Annex A of this report fall into three broad areas: carbon capture, storage and utilisation; sub-surface energy activities; and underpinning research challenges. Table 1 maps these on to the IEA nomenclature. Geothermal, although a renewable energy source, was also included within the scope of this workshop as relevant skills in the geological/earth sciences are also applicable in this area. The subject of methane hydrates was also covered briefly.

1 https://workspace.imperial.ac.uk/rcukenergystrategy/Public/reports/Final%20Workshop%20Reports/Fossil%20Fuels%20and%20CCS%20Working%20Paper%20Final.pdf

2 http://www3.imperial.ac.uk/rcukenergystrategy/prospectus

3 http://www.epsrc.ac.uk/SiteCollectionDocuments/Publications/reports/ReviewOfEnergy2010PanelReportFinal.pdf

4 http://ec.europa.eu/research/energy/pdf/statistics_en.pdf

Table 1: Mapping of this report's coverage against the IEA R&D Nomenclature

<table>
<tr><th>IEA Nomenclature</th><th>Carbon Capture, Storage and Utilisation</th><th>Sub-surface energy activities</th><th>Underpinning research</th></tr>
<tr><td>II.1.1 Enhanced oil and gas production</td><td></td><td>Secondary and tertiary recovery of oil and gas, and
Hydro fracturing techniques.</td><td></td></tr>
<tr><td>II.1.2 Refining, transport and storage of oil and gas</td><td></td><td>Submarine large-scale storage units</td><td></td></tr>
<tr><td>II.1.3 Non-conventional oil and gas production</td><td></td><td>Advanced drilling technologies</td><td></td></tr>
<tr><td>II.2.2 Coal combustion</td><td>Readying of combustion technologies to incorporate carbon dioxide (CO_2) capture and storage</td><td></td><td></td></tr>
<tr><td>II.2.3 Coal conversion</td><td></td><td>Underground coal gasification</td><td></td></tr>
<tr><td>II.3.1 Carbon Capture and separation</td><td>Absorption
Adsorption
Cryogenic separation
Membranes
Oxygen combustion
Hydrogen/syngas production
Chemical looping
Direct capture of CO_2 from air</td><td></td><td></td></tr>
<tr><td>II.3.2 Carbon transport</td><td>Carbon transport</td><td></td><td></td></tr>
<tr><td>II.3.3 Carbon storage</td><td colspan="2">Deep saline aquifers
Deep unminable coalbeds
Mineralization
Oil and gas reservoirs and
Monitoring and verification of stored CO_2</td><td></td></tr>
<tr><td>III.5 Geothermal energy</td><td></td><td>Hot dry rocks
Hydro-thermal and
Geothermal heat applications</td><td></td></tr>
<tr><td>VII.1Energy systems analysis</td><td colspan="3">Environmental dimensions
Policy and regulation
Technology acceptance</td></tr>
<tr><td>Not specified</td><td></td><td>Methane hydrates and
Coal bed methane</td><td>Other underpinning geological sciences</td></tr>
</table>

Many of the technologies in Area II of the IEA nomenclature are mature and were not explicitly addressed in the workshop. Discussion of conventional oil and gas production and coal, apart from coal bed methane (CBM) and underground coal gasification (UGC), was almost entirely absent. Table 2 illustrates this point by taking the full list of relevant IEA energy research topics and comparing the extent to which they are currently covered in the UK research landscape (Section 3 of the report) and whether they feature in the research challenges and needs identified in Sections 5 and 6. This shows that UK academics and others do work on the more mature energy technologies but do so in practice through direct links with the private sector, with public support through other research schemes or with occasional support through the Research Council responsive modes.

Table 2: The Current UK Research Landscape and New Research Challenges

IEA RD&D category	Current landscape (Section 3)	Research Challenges (Sections 5-6)
Enhanced oil and gas production	Oil and gas	Sub-surface activities
Refining, transport and storage of oil and gas	Oil and gas	**Not covered**
Non-conventional oil and gas production	Oil and gas	Sub-surface activities
Oil and gas combustion	Oil and gas	**Not covered**
Oil and gas conversion	Oil and gas	**Not covered**
Other oil and gas	Oil and gas	**Not covered**
Coal production, preparation and transport	**Not covered**	Sub-surface activities (partly)
Coal conversion	Coal conversion	Sub-surface activities (UGC only)
Other coal	**Not covered**	**Not covered**
CO_2 capture/separation	CCS	CCS
CO_2 transport	CCS	CCS
CO_2 storage	CCS	CCS/Sub-surface activities
Geothermal	**Not covered**	Sub-surface activities

This report is structured as follows. Sections 2-4 provide the wider context within which research and training challenges are identified. Section 2 focuses on the possible role of fossil fuels and carbon capture storage (CCS) in future energy systems both globally and in the UK. Section 3 describes the current UK research landscape and capability levels. Section 4 reviews existing roadmaps and assessments of research and innovation needs. Sections 5-8 draw heavily on the Edinburgh workshop. Section 5 sets out high-level research challenges in the three areas upon which the workshop focused. Annex A extends Section 5 and delves more deeply into these research challenges and identifies specific research questions that need to be addressed. Section 6 focuses on the ways in which the research councils operate, how the research they support is conducted and underlying needs for research infrastructure and data collection/curation. Many of the conclusions are generic in the sense that they may be applicable beyond the fossil fuel and CCS area across the energy domain or even more widely. Section 7 addresses training provision. Section 8 addresses generic issues about the role of the research councils within the wider UK energy innovation system and EU/international engagement.

2. Current and future role of fossil fuels and CCS

2.1 Global perspectives

Fossil fuels dominate current energy systems and their use is well established (Figure 1). In 2010, fossil fuels accounted for over 80% of the world's primary energy supply. Oil had the largest market share in 2010 (32%) but the use of coal and gas has grown rapidly while oil use has not changed significantly in the last five years.

There have been rapid developments in the production of 'non-conventional' fossil fuels in recent years, notably tar/oil sands from Canada and shale gas in the United States. Figure 2 for example shows historic US natural gas supply and forward projections. Shale gas now meets approximately one third of gas demand, starting from almost zero a decade ago. Shale gas could meet 50% of a significantly increased US demand for gas by 2040.

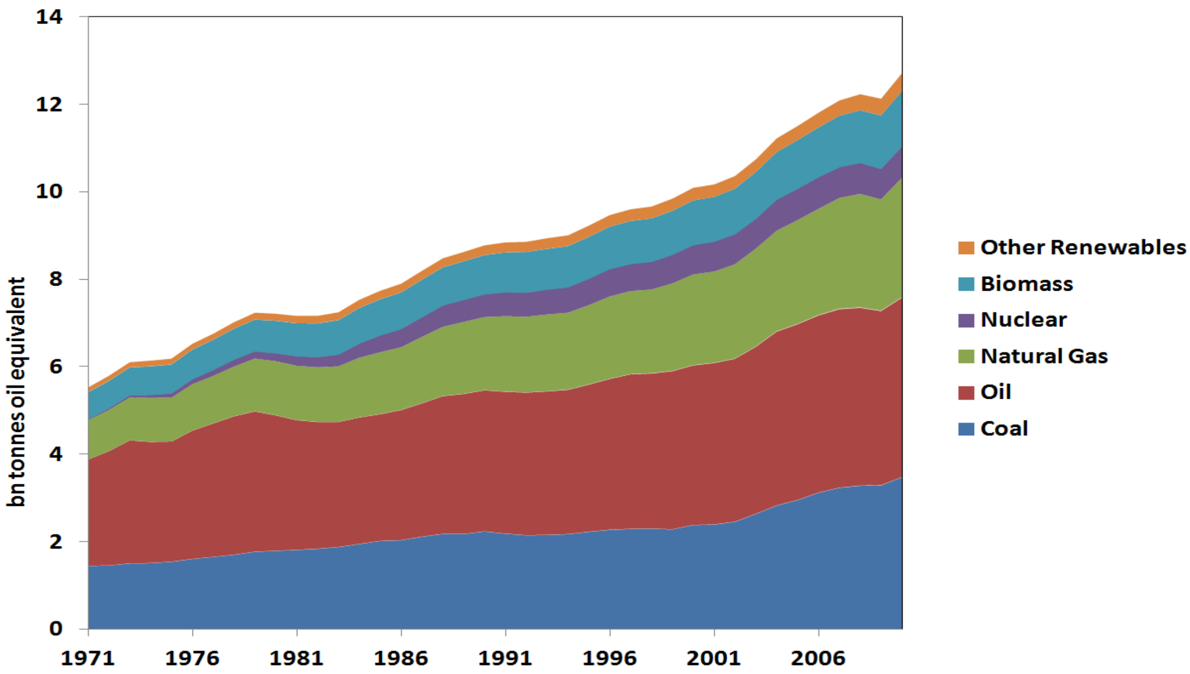

Figure 1: World Primary Energy Supply by Source
Source: IEA[5]

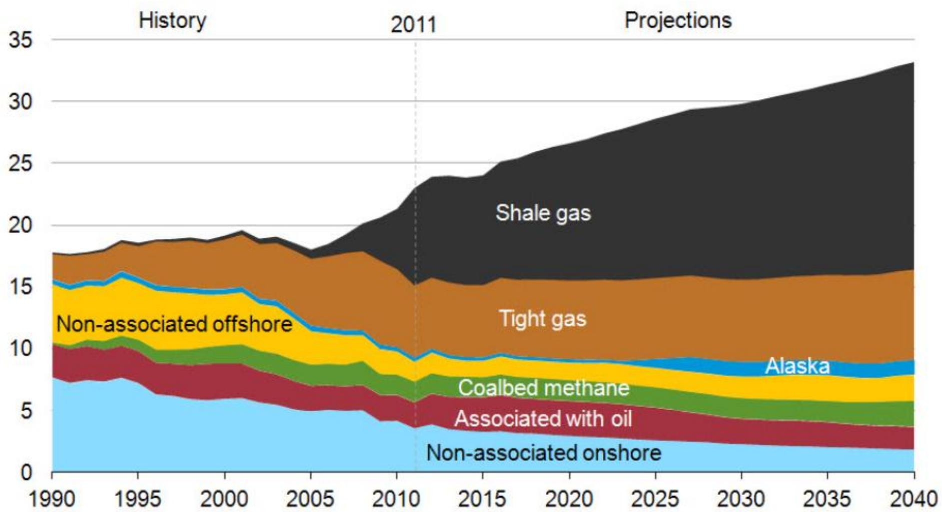

Figure 2: US natural gas projections
Source: Energy Information Administration (EIA)[6]

[5] International Energy Agency (2013): **Energy Statistics of OECD Countries** (Edition: 2013). Mimas, University of Manchester. DOI: http://dx.doi.org/10.5257/iea/eso/2013

The future of fossil fuels in future energy systems is not only highly uncertain but contested. Two broad types of scenario are currently in use: **normative** scenarios tend to be climate-driven and identify which combinations of technologies will meet the UN Framework Convention on Climate Change (UNFCCC) goal of keeping global temperature increases 2°C below pre-industrial levels; **exploratory** and **extrapolative** scenarios tend to embody lower levels of deployment of 'new' energy technologies and extend current trends in the use of fossil fuels into the future. Figure 3 compares two such scenarios, the IEA **two degrees scenario (2DS)** scenario[7] (normative) and the Shell **Mountains** scenario[8] (exploratory). In the IEA **2DS** scenario, global energy demand increases slowly and the use of coal starts to fall in the 2020s, while the market for oil has shrunk by 2050. Fossil fuels meet less than half of energy demand by 2050 being replaced by renewables and to a lesser extent nuclear. In the Shell **Mountains** scenario, demand for coal and gas increases by 2050, with oil demand falling after 2030. By 2050, the market share of fossil fuels has shrunk to two thirds of a greatly increased energy demand. The level of use of fossil fuels in 2050 varies by a factor of almost two between the IEA **2DS** and Shell **Mountains** scenarios.

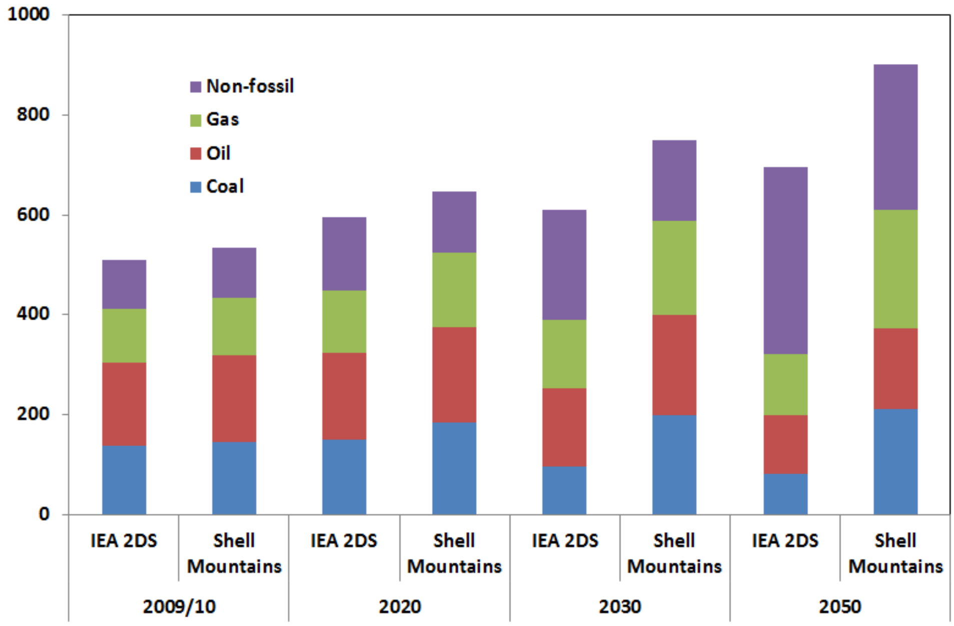

Figure 3: Primary Energy Demand in IEA Two Degrees and Shell Mountains Scenarios (EJ/year)
Source: International Energy Agency and Shell International BV

The Shell **Mountains** scenario would lead to a global temperature increase of at least 4°C,. CCS is a technology that could help to resolve some of the tensions between ambitious climate policies and the continued use of fossil fuels. Although the different components of CCS have been demonstrated, a complete system has yet to be demonstrated at scale. Many long-term assessments of energy futures conclude that CCS could play a crucial role in reconciling the continued large scale use of fossil fuels with ambitious policies to mitigate climate change. CCS has been identified as a 'game-changing technology' in energy scenarios that are compatible with meeting the UNFCCC goal of keeping global

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6 http://www.eia.gov/pressroom/presentations/sieminski_12052012.pdf

7 International Energy Agency, **Energy Technology Perspectives 2012: Pathways to a Clean Energy System**, Paris, 2012

8 Shell International BV, **New Lens Scenarios: A Shift in Perspective for a World in Transition**, 2013. http://s01.static-shell.com/content/dam/shell-new/local/corporate/Scenarios/Downloads/Scenarios_newdoc.pdf

temperature increases 2°C below pre-industrial levels, especially when combined with biomass energy (BECCS). Without CCS, considerably more expensive measures might be needed and the role of bioenergy in particular changes significantly.

2.2 UK perspectives

Three main tools are available for assessing long-term prospects for UK energy, greenhouse gas (GHG) emissions and technology deployment: the Department of Energy and Climate Change (DECC) 2050 Pathways Calculator;[9] the UK Energy Research Centre (UKERC) MARKet ALlocation (MARKAL) Model;[10] and the Energy Technologies Institute (ETI) Energy Systems Modelling Environment (ESME) model.[11] Each has distinctive features which enables them to address policy questions in a different way. The Pathways Calculator works through the consequences of technology deployment assumptions specified by the user. MARKAL and ESME select from a range of user-specified technologies to meet energy needs and GHG emission targets at least cost. In addition, ESME can treat key technology performance factors and costs in a probabilistic manner.

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

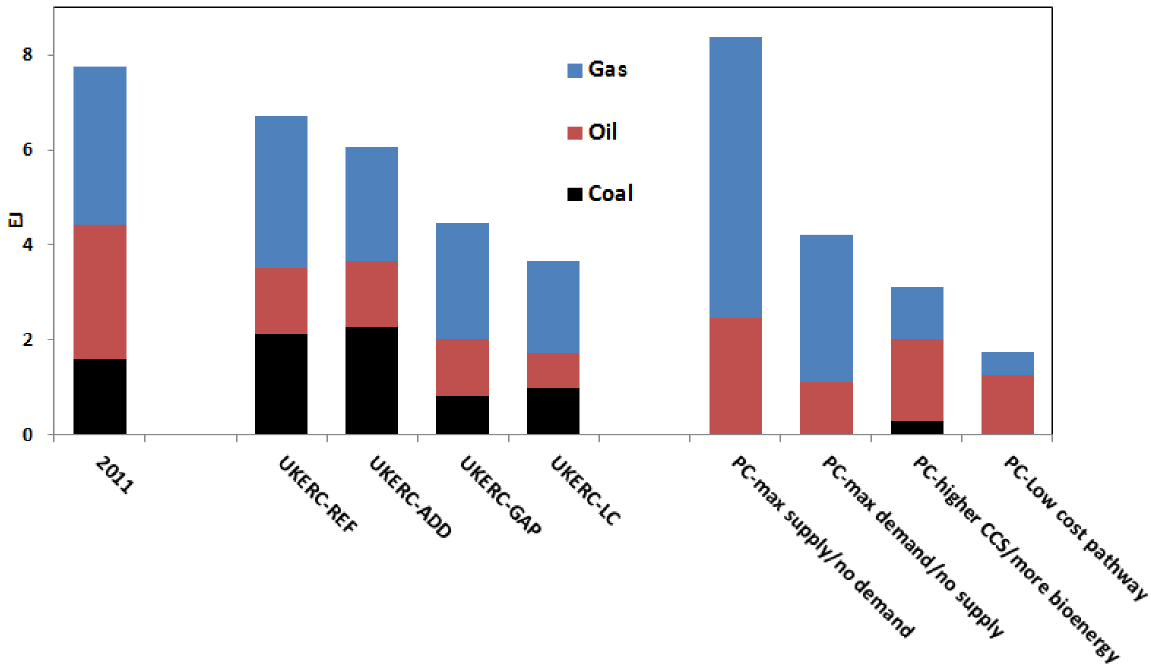

Figure 4: UK Fossil Fuel Use in 2050 in a range of scenarios

Figure 4 compares fossil fuel use in a set of MARKAL and Pathways Calculator runs with consumption levels in 2011. Only the **UKERC-LC**, **PC-higher CCS**/**more bioenergy** and **PC-low cost** pathway scenarios are compatible with the 80% target. The compliant Pathways Calculator runs result in very substantial reductions in the use of coal and gas whereas the **UKERC-LC** run reduces oil (mainly for transport) substantially and retains a considerable amount of gas. The runs that are non-compliant with the climate change target tend to use quantities of fossil fuels that are intermediate between today's

9 https://www.gov.uk/2050-pathways-analysis
10 http://www.ukerc.ac.uk/support/ES_MARKAL_Documentation_2010
11 http://www.eti.co.uk/technology_strategy/energy_systems_modelling_environment

level of use and those needed to hit the target. The very high level of fossil fuel use in the **PC-max supply/no demand** pathway is an artefact of the underlying technical assumptions and does not take into account existing policies that will reduce fossil fuel use.

It is reasonable to infer that fossil fuel use will decline in the UK but that there is a great deal of uncertainty as to how deep that decline will be and which of the three main fossil fuels will be affected most significantly.

Figure 5 shows that there is also a great divergence in projections of CCS deployment in different scenarios. The MARKAL scenarios indicate about 10 GW of CCS deployment in all scenarios, with the split between CCS on coal, gas and coal/biomass co-firing being scenario dependent. The assumptions underlying the Pathways Calculator runs vary from zero deployment of CCS through to 60 GW, with gas CCS dominating. The LCICG CCS Technology Innovation Needs Assessment (TINA) envisages 11-60 GW of CCS on the electricity system by 2050, with 30 GW in a medium scenario.[12]

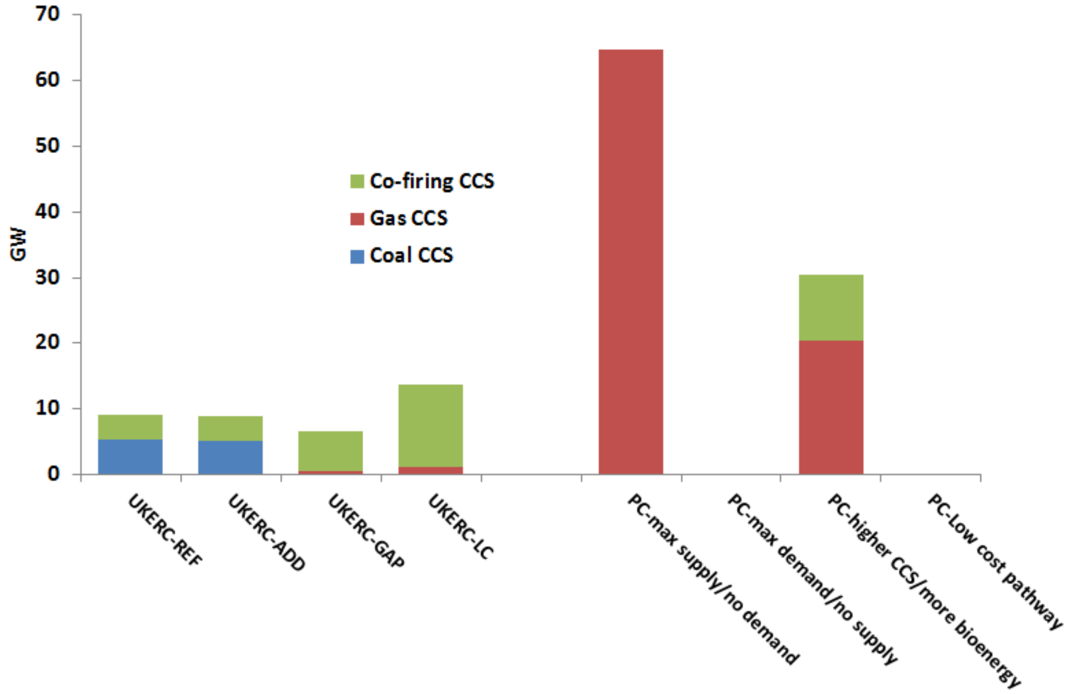

Figure 5: UK CCS Deployment in 2050 in a Range of Scenarios

As well as demand for fossil fuels in the UK, prospects for indigenous production are also relevant. Figure 6 shows that the production of coal in the UK has virtually ceased while production of oil and gas, mainly from the North Sea, is now in steep decline. This forms the background to current interest in production from non-conventional sources, e.g. shale gas.

12 Low Carbon Innovation Coordination Group, Technology **Innovation Needs Assessment (TINA) Carbon Capture & Storage in the Power Sector**, Summary report, August 2012. http://www.lowcarboninnovation.co.uk/document.php?o=5

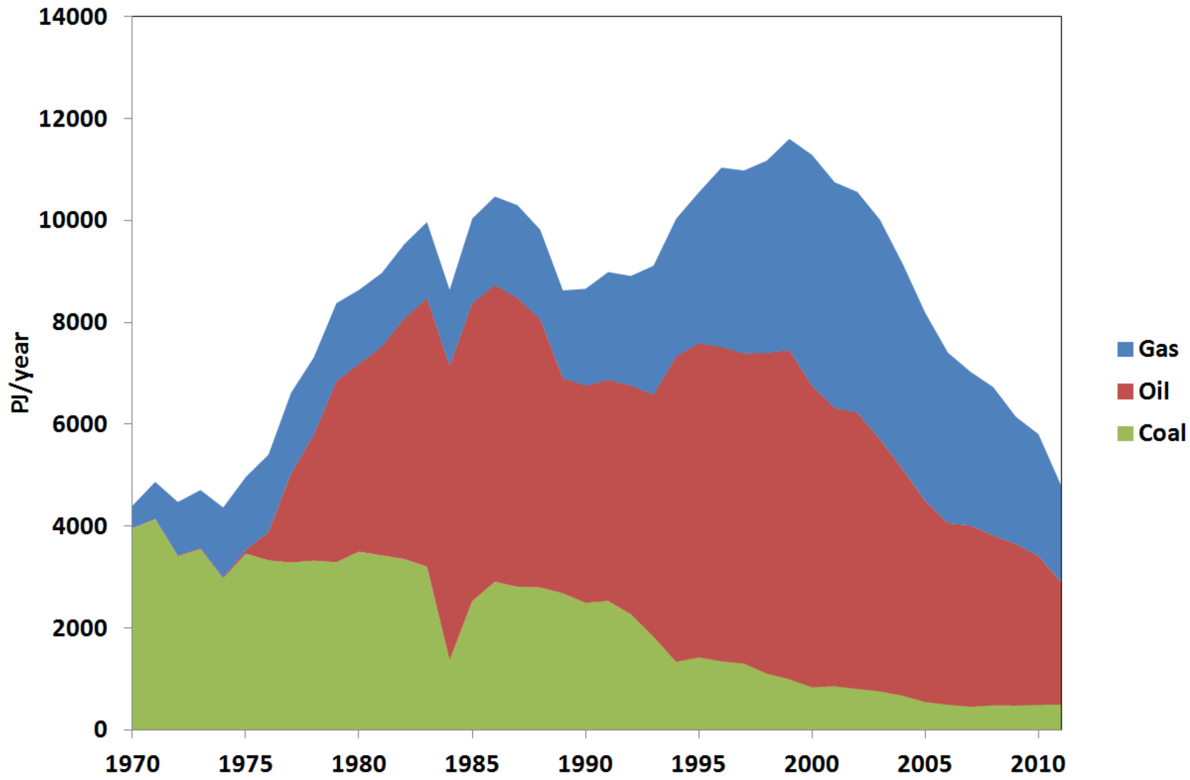

Figure 6: UK Indigenous Production of Fossil Fuels

2.3 Energy goals and expectations

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

This divergence has considerable implications for the role of fossil fuels. Figure 7 systematically compares participants' aspirations and expectations for electricity generation technologies in 2050. The green triangles indicate the market share of technologies in the 'preferred' mix, averaged over all participants, while the red triangles refer to the expected mix.[13] The lines refer to the range of responses from individual participants. Participants tended to trade off unabated gas versus renewable energy and other low carbon technologies in thinking about desired versus expected worlds.

Deployment of onshore wind and marine renewables was expected to be about half the desired level, whereas unabated gas was expected to have a 20% market share, as opposed to the desired level of zero. However, CCS with fossil fuels and nuclear actually had slightly higher expected shares compared to the desired levels. Thus, the level of expected fossil fuel use for electricity generation is higher than the desired level, but the difference is perhaps not as great as that derived from comparing global scenarios.

[13] The market shares add to more than 100%. This reflects the subjective nature of the workshop process and does not take away from the general point about the expectation/aspiration gap.

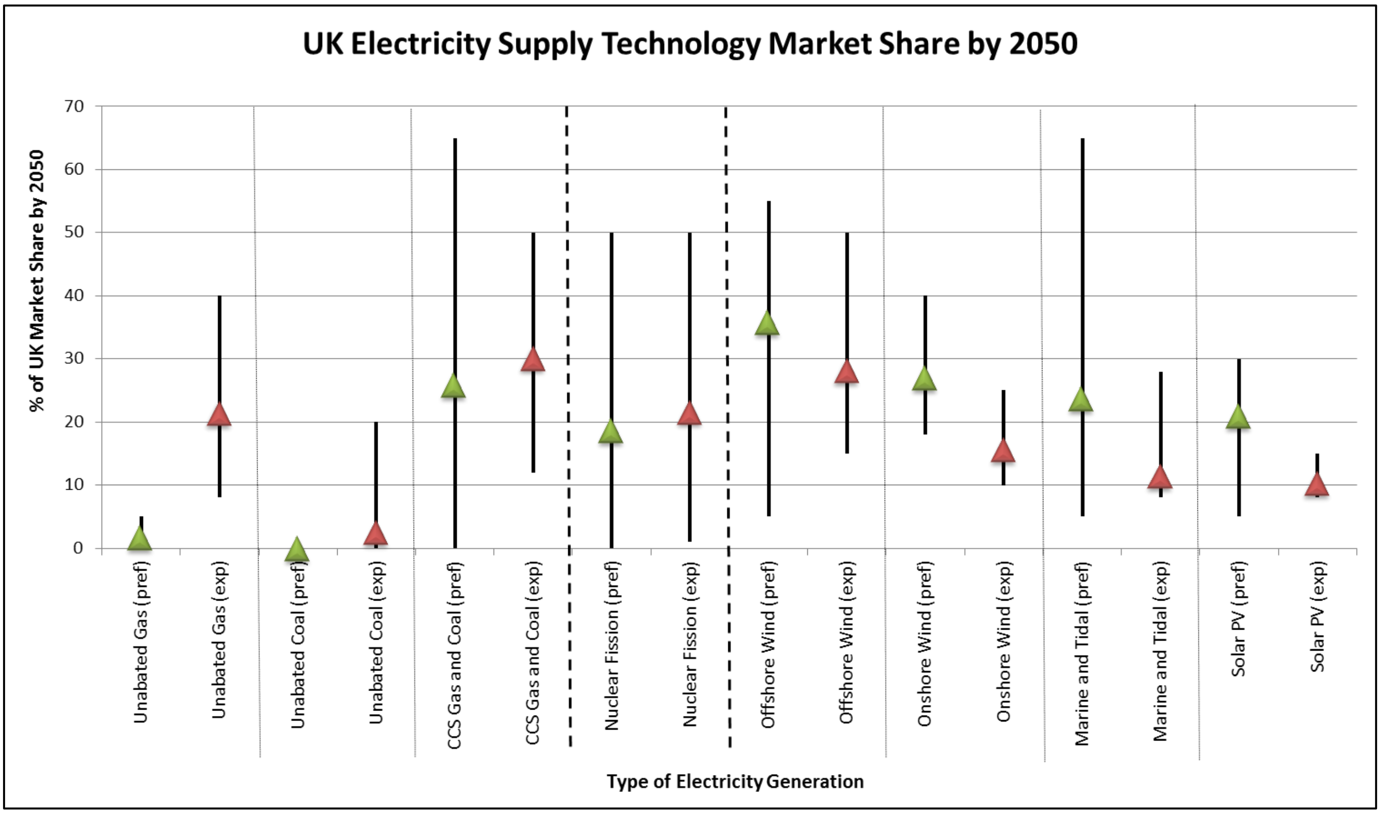

Figure 7: Preferred (green) and expected (red) ranges and mean average values for electricity supply technologies

2.4 Conclusions

There is a divergence between: a) the roles foreseen for fossil fuels in different energy scenarios, at both the global and UK levels; and b) the aspirations and expectations of the UK energy research community. Furthermore, CCS is a potentially game-changing technology, again with major divergences across different energy scenarios both in the UK and globally. The research councils need to plan their portfolios in the fossil fuel/CCS area with full regard to these uncertainties. Specifically, portfolios should prepare for the possibility that new sources of fossil fuels may be needed to meet higher projected levels of demand and that there may be major deployment of CCS to reconcile the continued large-scale use of fossil fuels with climate policy goals.

3. Current UK research capabilities

3.1 Overview

This section is based on three sources of evidence: a) subjective judgements made at the first strategic workshop about UK research and industrial capabilities in relation to fossil fuels and CCS as well as other energy areas; [14] b) subjective judgments of UK research capability levels made at the expert

[14] https://workspace.imperial.ac.uk/rcukenergystrategy/Public/reports/Energy%20strategy%20fellowship%20 Report%202%20%20-%20Energy%20strategies%20and%20energy%20research%20needs%20FINAL.pdf

workshop; and c) peer-reviewed assessments of UK R&D capabilities documented through the UKERC Energy Research Atlas 'landscape' documents.[15]

A number of workshop participants found Figure 8 helpful in conceptualising the close relationship between capabilities relating to the extraction and use of fossil fuels and those relating to CCS. Traditionally, skills in geology, earth sciences and petroleum engineering have been associated with 'upstream' extractive fossil fuel activities. Mechanical and chemical engineering have been associated with the conversion of fossil fuels (e.g. in refineries) and combustion (e.g. in power stations). These same disciplines are key in developing CCS, except that mechanical/chemical engineers play a role in the carbon capture space (which is now 'upstream' in terms of carbon flow) while the geological sciences are associated with 'downstream' storage of carbon. This diagram illustrates how common skills can be applied across the fossil fuel and CCS domains, the implications of which for training are picked up in Section 7 of this report.

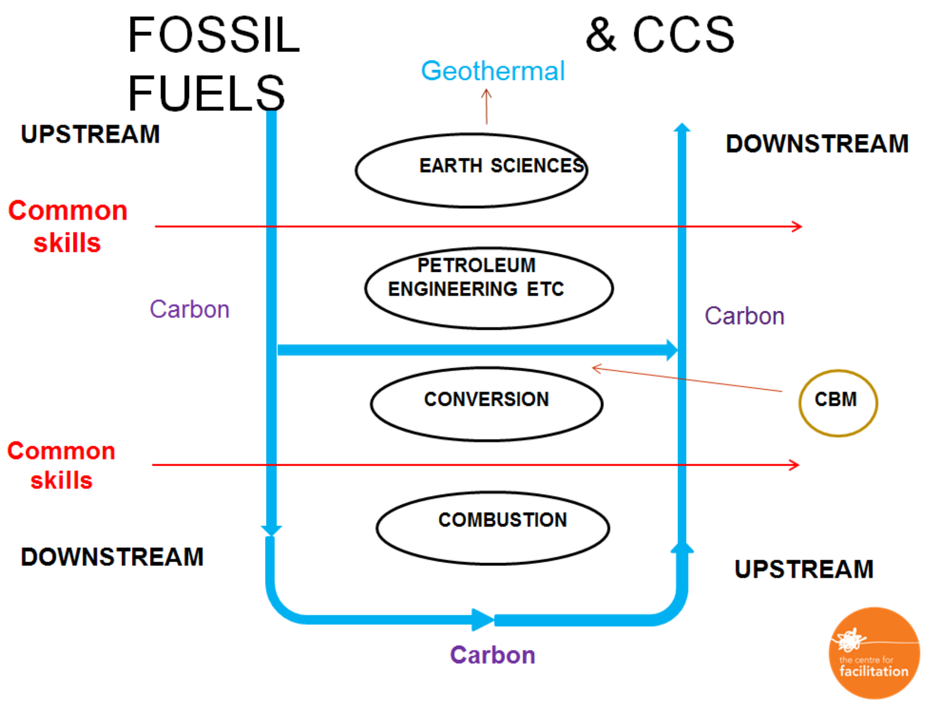

Figure 8: Conceptual diagram to illustrate the relationship and overlap between the fossil fuel and CCS skillsets

3.2 Strategic workshop

Figure 9 was one of the outputs of the strategic workshop on UK research and industrial capabilities. This plots subjective judgments as to how the UK's industrial capabilities in specific areas of energy research are mapped against 'relevance to UK energy futures' (environment, affordability, security, economic opportunity). The size of the 'blobs' represents a subjective judgment about the level of scientific capability in the UK. Topics relevant to this report are mapped in red. Research areas to the left of the vertical axis represent areas where there is thought to be no clear international lead, or that one has yet to be established.

15 http://ukerc.rl.ac.uk/ERL001.html

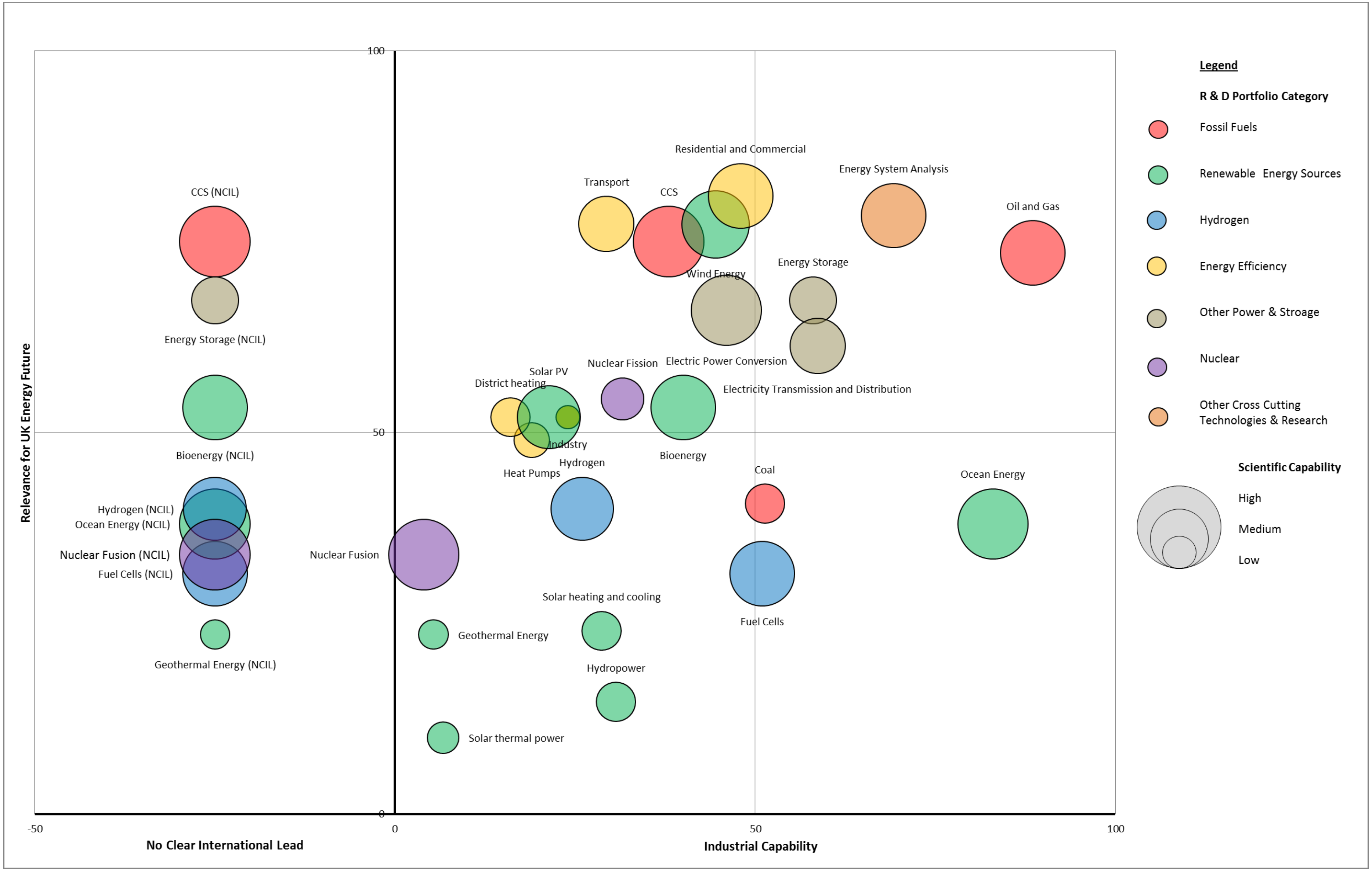

Figure 9: The UK's current and future energy R&D portfolio

The UK was judged to have high scientific and industrial capabilities in relation to oil and gas. This was attributed to experience gained during the exploitation of North Sea reserves. Oil and gas were also perceived to be highly relevant to UK energy futures. Coal on the other hand was seen to be less relevant to the UK's energy future and to be underpinned by middling scientific and industrial capabilities. The UK was seen to be scientifically strong in relation to CCS which was also seen to be highly relevant to the UK's energy future. However, there was less agreement about the UK's industrial capacity. There were those who believed that the UK's capability was relatively low while others thought that no clear international lead in CCS technology had been established. Geothermal energy featured very low in terms of scientific capability, industrial capability and relevance to the UK's energy future.

3.3 Expert workshop

Participants at the expert workshop were asked to score on a scale of 0-10 how well they thought the UK was now equipped in terms of research capabilities for tackling future challenges in the area of fossil fuels and CCS. At the start of the workshop, 24% of comments gave the UK a high score (7-10), 47% a medium score (4-6) and 29% a low score (0-3). The average score was 4.9.

Although the scores diverged, qualitatively there was more consistency across the supporting comments. The majority of comments concerning individual technology areas referred to CCS with a few relating to oil and gas. A common theme was that the belief that scientific capabilities in the community were high but that these would be fully exploited only if there was greater systems integration across the CCS chain, greater joining up across the research councils and clearer policy direction. More specifically, the UK was seen to have strengths in the system simulation of CCS and CO_2 capture technology and medium capabilities in the monitoring and verification of stored CO_2. Some perceive weaknesses in terms of knowledge and techniques relating to deep onshore geology but this is disputed.

3.4 UKERC research landscape

The UKERC Energy Research Atlas has four landscape documents falling within the scope of this report: 1) oil and gas; 2) coal conversion; 3) coal combustion; and 4) CCS. The following discussion combines the coal combustion/conversion topics.

3.4.1 Oil and gas

At the first Fellowship strategy workshop, the oil and gas area was deemed to be one in which the UK had the greatest commercial capability combined with a high level of scientific capacity (Figure 9). This view is supported by UKERC Energy Research **Oil and gas** Landscape document.[16] R&D capacity was firmly established during the development of the North Sea and has enabled the UK to compete effectively in international markets.

Given this legacy, and perhaps because R&D requirements in this field tend to be applied in nature, oil and gas does not feature explicitly in either the RCUK Energy Programme portfolio, nor under the EPSRC energy theme. Oil and gas conversion and combustion (downstream activity) is implicitly covered in the EPSRC conventional generation and combustion area. It is planned that investment in this area will be reduced relative to others in the portfolio given the relative maturity of this area and an expected decreasing role in the UK energy mix. This view was challenged in the course of the workshop in respect of upstream extractive activities.

[16] http://ukerc.rl.ac.uk/Landscapes/OilandGas.pdf

There is very significant private sector investment in R&D on the part of UK oil and gas producers. This was estimated to amount to about £1,000 million in 2009.[17] There is wide-ranging expertise in engineering and technology firms undertaking product development in exploration, production (including sub-sea systems), process analysis and controls and instrumentation.

UK R&D is supported by a range of disciplines including combustion, materials, fluid dynamics and heat transfer processes. The UKERC Energy Research Landscapes lists 190 oil and gas projects spread between 47 universities and institutes covering the following topics:

- hydrocarbon reservoir related research for resource extraction performance or gas storage: geosciences, geology, geochemistry, seismology, seismography;
- marine: wave loading, structural engineering and sedimentology;
- process performance and energy efficiency: fuel research and combustion, tribology, energy modelling, asset life time analysis, automotive engines, drilling, hydrocarbon processes; and
- fundamental Enabling topics in support of other activities:
- fluid flow/dynamics, numerical modelling, energy research capacity, data and information systems
  - instrumentation and measurement, gas spectroscopy
  - materials: strength of materials, corrosion, non-destructive evaluation, membrane technology.

UK capabilities are assessed to be high across the board, with slightly less pronounced strengths in: separation processes and membrane technology; thermodynamics of power and process plant; instrumentation; chemical engineering; and advanced materials for process applications.

3.4.2 Coal conversion and combustion

Participants in the strategic workshop saw these areas as being characterised by low scientific capability, medium industrial capability and having relatively little relevance to UK energy futures. The topics received little attention at the expert workshop.

The UKERC landscape documents on coal conversion[18] and coal combustion[19] note that the UK was once considered a world leader in these fields, but that this leadership has been eroded in recent years. Nevertheless, the UKERC landscape documents note high levels of residual competence relating to turbine and combustion technology and coking techniques. The UKERC CCS landscape[20] (see below) notes that the UK is strong on supercritical coal and (potentially) ultra-supercritical coal plant. Expertise in relation to CBM, UCG and gasification technologies is viewed as middling. Competences in respect of coal liquefaction are deemed to be low.

The main support for research in these areas is channelled through EPSRC responsive mode funding and the Biomass and Fossil Fuel Research Alliance (BF2RA), which was established in 2009 and is also in receipt of EPSRC funding. The British Coal Utilisation Research Association (BCURA) ceased to conduct research in 2011. European support for research in these areas comes not through the EU Framework Programmes but through the Research Fund for Coal and Steel (RFCS) which was established following the expiry of the European Coal and Steel Community (ECSC) Treaty in 2002.

Active research groups fall into four groups: practice-based groups whose activities include small scale test-work and associated modelling; environmental sciences groups concerned with the monitoring and

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[17] **The 2010 R&D Scoreboard: The Top 1000 UK and Global Companies by R&D Investment**, Department for Business, A very large Innovation & Skills, 2010
[18] http://ukerc.rl.ac.uk/Landscapes/Coal_Conversion.pdf
[19] http://ukerc.rl.ac.uk/Landscapes/Coal_Combustion.pdf
[20] http://ukerc.rl.ac.uk/Landscapes/CO2CS.pdf

evaluation of emissions; groups concerned with the techno-economic aspects of coal conversion; and groups applying social science assessment techniques to coal conversion. There are strong industrial connections in this field. Many researchers in these fields have diversified or moved over to conduct work on biomass conversion and combustion and carbon capture.

In general, this field has the characteristic of one that has fallen 'out of fashion' in terms of public research funding but still retains a core of competent applied research supported mainly through commercial links.

3.4.3 Carbon capture and storage

Participants in the strategy workshop believed that the UK had strong scientific capabilities in the CCS field though there was less agreement about industrial strengths. They noted that there is still much to play for internationally. CCS was seen as highly relevant to UK energy futures.

Participants in the expert workshop devoted significant amount of time available to the consideration of CCS. Broadly, capability levels were deemed to be high but discussions reflected the view of the expert workshop that the potential contribution of the science base depended on larger-scale integration and policy efforts.

The UKERC CCS Landscape document[21] was last updated in 2009 and consequently much of the detailed information is out of date. However, the assessment of underlying capabilities remains valid.

The UK is seen to have high levels of capability in terms of: subsurface geological and engineering; coal-fired supercritical boilers; oxyfuel burners; air separation units for oxyfuel; turbines: gas and steam; onshore pipes; offshore pipes; project finance; carbon trading; and the design of capture add-ons.

There are medium capability levels for: coal-fired power stations; gas-fired power stations; CO_2 compression; offshore enhanced oil recovery mechanical and geo-engineering; and solid fuel gasifiers.

Capabilities are low for: membranes for separation of CO_2 and oxygen; solvent CO_2 capture; CO_2 pipelines; and the design of 'capture ready' add-ons.

Much of the research councils spend in this area is channelled through the UK Carbon Capture and Storage Research Centre (UKCCSRC) [22] which runs a Community Network of about 900 scientists and administers a flexible research fund.

3.4.4 International activities

The UK is active in international activities which leverage domestic R&D investments. **Oil and gas** R&D, is largely conducted in the private sector. The UK hosts two oil majors, Shell and BP, whose R&D activities have a global remit. The British Geological Survey (BGS), part of NERC, also operates internationally with many overseas clients. The UK participates in an IEA Implementing Agreement on **Enhanced Oil Recovery**.

The UKERC Landscape documents on **Coal Combustion** and **Coal Conversion** note that the UK is active in a number of EU FP7 and Research Fund for Coal and Steel (RFCS) projects on topics such as materials for ultra-high efficiency power plants, integrated gasification combined cycle, underground coal gasification biomass co-firing and other aspects of combustion. The UK hosts two IEA Implementing Agreements, the **Clean Coal Centre** and the **Greenhouse Gas R&D Programme**.

[21] ibid

[22] http://www.ukccsrc.ac.uk/

The UK has been involved in extensive collaborations on **CCS** under most of the main projects funded under the EU FP7 and FP6 programmes. These include those relating to carbon capture (DECARBIT, CESAR, CAESAR, CACHET), carbon storage (CASTOR, CO2REMOVE, CO2SINK, CO2GeoNet) and the regulation of CCS (STRACO2). The UK also participates in a number of relevant networks run through the IEA **Greenhouse Gas R&D Programme**, EU technology platform **ZEP** (Zero Emissions Platform) and the international **Carbon Sequestration Leadership Forum** (CSLF).

4. Existing roadmaps and innovation needs assessments

4.1 Introduction

Recent roadmaps and needs assessments, in the UK and internationally, have focused almost exclusively on CCS. The major exception is the IEA geothermal roadmap published in 2011. Section 5 and Annex A of this report identify a range of research needs associated with fossil fuel extraction, notably with unconventional hydrocarbons such as shale gas. The public sector has so far played little role in this area and no relevant roadmaps have been identified. However, the need for R&D has been identified and, in the US, three agencies – the Environmental Protection Agency (EPA, covering air and water quality, health and environmental risks), the US Geological Survey (USGS, covering resource assessment, hydrology and geology, land use, wildlife, and ecological impacts) and the DOE (covering wellbore integrity, flow and control, green technologies, systems engineering, imaging and materials) – have established a Memorandum of Understanding on R&D for unconventional oil and gas.[23]

4.2 CCS - UK

There are two UK specific assessments. The summary report of a TINA conducted through the LCICG[24] focuses specifically on CCS for the power sector. The full assessment has not yet been published. Like other TINAs, much of the assessment focuses on the case for public sector investment in research, development and demonstration (RD&D). The report concludes that the 'option value' of having CCS available to meet the UK's 2050 GHG emission reduction targets is very high, in excess of £100bn over the period 2010-2050. The case is made for investment in R&D of the order of hundreds of millions of pounds over a five to ten year period and investment of low billions of pounds in full-scale demonstration projects. It is concluded that innovation could cut the costs of CCS deployment significantly and that the UK could play a significant role in a global CCS market.

The report addresses the extent to which the UK needs to drive innovation itself or can rely on other countries' innovation efforts. There are needs specific to the UK in the areas of carbon transport and carbon storage, including measuring, monitoring and verification (MMV) and mitigation and remediation (M&R). There could be competitive advantage arising from work on capture components, specifically those relating to natural gas, biomass and full system integration. The case for innovation support is weaker in relation to coal combustion, combined cycle gas turbines (CCGTs) and CO_2 compression.

The report identifies at a high level a number of areas of innovation support that are possible priorities. These include:

- full-scale demonstration of and integrated capture/transport/storage chains;
- deep sub-sea storage and MMV;
- retrofit coal, gas and biomass components and their integration;
- multi-fuel gasification and capture components and their integration;

23 http://unconventional.energy.gov/pdf/oil_and_gas_research_mou.pdf
24 http://www.lowcarboninnovation.co.uk/document.php?o=5

- advanced conversion concepts, e.g. oxyfuel combustion, with CCS;
- MMV associated with demonstration projects; and
- optimised operation of plants with CCS.

The report identifies three R&D priority areas at or before the proof-of-concept stage that are relevant to the research councils. These are:

- 'breakthrough' capture concepts addressing performance and cost challenges;
- mitigation and remediation (M&R); and
- geological characterisation and performance simulation linked to MMV.

In the latter, case the report specifically notes that the research challenge could be identified through demonstration work.

UKERC, along with the UK Carbon Capture and Storage Consortium (UKCCSC), produced a CCS roadmap in 2007.[25] This document was essentially a deployment roadmap focusing largely on needs in terms of policy, regulation, legal aspects and standardisation. The document emphasised the need for policy certainty and stability. Most of the substantive research recommendations referred to integration along the CCS chain and issues related to carbon storage.

4.3 CCS - EU

The European Industrial Initiative (EII) on CCS developed a roadmap and corresponding implementation plan in 2009 under the Strategic Energy Technology (SET) Plan.[26] This identifies a number of:

- fossil fuel conversion technologies aimed at improving power plant efficiency;
- capture technologies aimed at improved efficiency and cost-effectiveness and their better integration in power generation, e.g. research on new components and technologies, such as solvents and membranes;
- transport and storage concepts aimed at identifying and quantifying storage capacities in Europe as well as injection and monitoring technologies to track CO_2 in underground reservoirs and to detect leaks; and
- use of CCS technologies in other industrial sectors such as cement, steel, refineries, etc.

4.4 CCS - International Energy Agency

The IEA published a CCS roadmap in 2013.[27] This replaced documents focusing specifically on CCS for power generation[28] and industrial applications.[29] The focus is specifically on actions needed to accelerate CCS deployment consistent with limiting the average global temperature increase to 2°C. As in the LCICG TINA, CCS is identified as a key technology for achieving long-term GHG emission reduction goals.

Given the nature of the report, the emphasis is on the establishment of the policy and regulatory frameworks required for deployment. However, a number of RD&D challenges are specifically identified:

25 http://ukerc.rl.ac.uk/Roadmaps/CarbonCapture/CCS_road_map_workshop_Aug08.pdf
26 http://setis.ec.europa.eu/system/files/CCS_EII_Implementation_Plan_final.pdf
27 http://www.iea.org/publications/freepublications/publication/CCS_Roadmap.pdf
28 http://www.iea.org/publications/freepublications/publication/name,3847,en.html
29 http://www.iea.org/roadmaps/ccs_industrial_applications.asp

- reducing the cost of electricity from power plants equipped with capture through continued technology development and use of highest possible efficiency power generation cycles;
- proving capture systems at pilot scale in industrial applications where CO_2 capture has not yet been demonstrated;
- supporting research into novel capture technologies and power generation cycles that will dramatically lower the cost of capture and resource consumption; and
- encouraging R&D into innovative and novel processes that will reduce the cost of CCS.

In addition, the report advocates increasing international RD&D collaboration.

4.5 CCS - other international reports

The US Department of Energy has prepared a comprehensive RD&D roadmap for CCS (2010) through the National Energy Technology Laboratory (NETL).[30] The report identifies climate change as being the major driver for CCS. An extensive set of RD&D needs is identified using the following framework:

CO2 capture and compression:

- pre-combustion CO_2 capture – advanced technology approaches;
- post-combustion CO_2 capture – advanced technology approaches;
- oxy-combustion CO_2 capture – advanced technology approaches;
- chemical looping combustion; and
- CO_2 compression.

CO_2 transportation

CO2 storage:

- improved fundamental understanding; and
- technology development.

Monitoring, verification, and accounting:

- atmospheric and remote sensing;
- near-surface monitoring;
- wellbore monitoring;
- deep subsurface monitoring; and
- accounting protocols.

Simulation and risk assessment:

- mathematical models development/verification; and
- improved risk assessment protocols.

4.6 Geothermal energy

The IEA has produced the only widely available roadmap covering geothermal energy.[31] This was largely a deployment roadmap, but it did advocate: the development of publicly available databases, protocols and tools for geothermal resource assessment and on-going reservoir management to help spread expertise and accelerate development; and the provision of sustained and substantially higher RD&D resources to plan and develop at least 50 more enhanced geothermal systems pilot plants by 2020.

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30 http://www.netl.doe.gov/technologies/carbon_seq/refshelf/CCSRoadmap.pdf
31 http://www.iea.org/publications/freepublications/publication/name,3992,en.html

In addition, it made the following specific RD&D recommendations:

- development of databases, protocols and tools for geothermal resource assessment;
- development of new and more competitive drilling technology as well as downhole instrumentation;
- increase efficiency and performance of geothermal combined heat and power (CHP) and expand possibilities for geothermal heat use;
- improve enhanced geothermal systems technology and development of efficient reservoir creation and management methods;
- improve management of health, safety and environmental issues, including risks associated with induced seismicity, in enhanced geothermal systems development; and
- explore feasibility of alternative hydrothermal and alternative hot rock technology.

5. High-level research challenges

The research challenges identified in the fossil fuel and CCS area fall into two broad application areas:

- carbon capture, storage and utilisation; and
- energy production from sub-surface resources.

There are underpinning basic research challenges that cut across the first two application areas, notably in the geological sciences. Environmental, social and economic aspects also cut across all application areas.

Many of these research challenges are not unique to the UK. Given the large scale of the R&D activities required in the fossil fuel and CCS domain, challenges that are common across countries may best be pursued internationally rather than through the UK acting alone. Other research challenges, such as those relating to resource characterisation and regulatory design, are UK-specific. As noted in Section 3, much of the R&D in the fossil fuel area is of an applied nature relating to the improvement of mature technologies and techniques. R&D is conducted by private companies in whom the intellectual property (IP) resides. The main role of public sector R&D is to develop generic knowledge regarding resources and their characterisation, develop and advance pre-commercial technologies, respond to basic science and engineering problems suggested by technology demonstration and deployment, and support the regulation of the sector. Some of these public sector tasks are within the remit of the research councils and some are not. The research councils also have, as required under their Royal Charters, a role to play in ensuring the provision of qualified scientists and engineers.

Table 3 and 4 show research challenges related to carbon capture, storage and utilisation and sub-surface energy activities respectively. There is some overlap between the categories in relation to carbon storage. Since CCS is considerably less mature than fossil fuel exploitation in general, there is a greater role for more basic/strategic research in that area. The CCS research challenges identified are more numerous and also delve into more detail. This reflects the degree of attention focused on this topic at the Energy Strategy Fellowship expert workshop and is not necessarily an indication of greater priority. Fossil fuel *utilisation* received less attention. This reflects a waning of interest among both funders and researchers, many of whom have migrated towards biomass utilisation and/or carbon capture technology. EPSRC's 'conventional generation' sub-theme, which covers this area, has been designated for reduced funding.

'Energy from the subsurface' (Table 4) covers a wide range of topics including unconventional fossil fuel production (e.g. shale gas), methane hydrates and geothermal energy. The UK is perceived to have considerable scientific and industrial strengths in relation to oil and gas in general, but weaknesses in relation to more specific topics such as UGC, CBM and geothermal energy.

Table 5 shows challenges of a more underpinning scientific nature, all of which are potentially within the remit of the research councils. Many of the opportunities are within the remit of the geosciences, and hence NERC, with a wide range of applications across energy production and carbon storage. There is a need for interdisciplinary research relating to sub-surface engineering. Other areas of research opportunity include engineering for new materials and scalable technology, economic and social research covering regulation and risk management, and research into the environmental impacts of energy activities.

Table 3: Research challenges in the area of carbon capture, storage and utilisation

	Challenge	**Notes**
Development and demonstration (including some supporting basic research)	CO_2 capture retrofit for gas-fired generation	
	CO_2 capture and utilisation for producing fuels and chemicals	
	Co-location of CO_2/liquefied natural gas (LNG) shipping	
	Monitoring and control of carbon storage pilot	
	Reliability, availability, maintainability and operability (RAMO)	
Applied and basic research	Next generation CO_2 capture: membranes; adsorbents; carbon looping	
	Low-cost CO_2 corrosion inhibitors	
	Small scale carbon capture	
	Negative emissions technologies	Including biomass energy with CCS (BECCS)
	Biomimetic CO_2 capture/transport/storage	
	Air capture of CO_2	Including environmental effectiveness
	CO_2 storage capacity	
	Security and safety issues related to CO_2 storage	
	Legal constraints	
	Economic dimensions	
	Public perceptions and acceptability	
	Health implications of chemicals for carbon capture and transport	

Table 4: Research challenges related to sub-surface energy activities

	Challenge	Notes
Applied R&D	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	
	Enhanced oil recovery using CO_2	Linked to CCS
	Security and safety issues related to methane	
	UCG	The UK is weak in this area industrially and scientifically
	CBM	The UK is weak in this area industrially and scientifically
	Geothermal energy	Including monitoring and control of pilot activities. The UK is weak in this area industrially and scientifically. But need for UK-focused research and technology development?
Applied and basic research	Public attitudes to and social acceptability of shale gas/hydraulic fracturing	
	Legal constraints	
	Economic dimensions	
	Methane hydrates	

Table 5: Underpinning research challenges

Area	Challenge	Notes
Geosciences	Complex characterisation of subsurface systems	Multiphase reactive and flow properties of the sub-surface as CO_2, brine and hydrocarbons flow through. NERC/EPSRC interest.
	Fluid-rock interactions	
	Flow characterisation at large spatial and temporal scales	
	Impacts of engineered activity on the deep sub-surface	Pressure management, space, efficiency, safety, security, heat NERC/EPSRC interest
Engineering	Novel structural materials for power plants, capture units, pipelines	
	Cost reduction and scalability of technology to meet user needs	
Economics and social science	Market reform; legal and regulatory issues	
	Risk mitigation for underground exploitation	
Environmental science	Environmental and ecosystem service impacts associated with energy production from the sub-surface and CCS.	Includes both normal operation and the risk of accidents
	Life cycle assessment of smart materials and structures	

Further development of the high-level research challenges suggested in Table 3-5 is needed to establish concrete research plans. Bodies such as the UKCCSRC have a role to play in undertaking this task. Given the deep uncertainties, identified in Section 2, about the deployment of specific technologies in the coming decades, the development of portfolios of research activity that can be adapted in the light of changing priorities and new knowledge would be advisable. Annex A identifies in more detail the research needs that could be covered by future activities.

6. Research support

This section covers a range of issues concerning the way in which research in the fossil fuel and CCS areas is supported and conducted. These issues were raised in the Energy Strategy Fellowship expert workshop and are offered as potential ways of improving the effectiveness of research. Most of the issues raised have implications wider than this particular research domain.

6.1 Ways of working

Cross-Council working. Fossil and fuel and CCS research is supported by both EPSRC and NERC and there is a perceived need for them to work together effectively. More projects should be supported on a cross-research Council basis to fulfil this aim. Pilot CCS projects will provide a valuable source of research opportunities and data. The research councils should link into pilot and demonstration projects to secure the involvement of their research communities.

Collaboration between investments. The community in the fossil fuel field is felt to be fragmented and current research programmes are poorly integrated. Critical mass is essential. Centre funding would help to overcome this problem.

Funding processes. Consultation in developing research agendas is highly valued by the community. There is a strong view that research would be more productive if it achieved critical mass by focusing on thematic programmes, large scale consortium projects, research hubs and centres. Existing investments could be allowed to bid for additional funding to build up collaborative arrangements. There have been considerable achievements in fostering research communities and these should be built upon. However, there is concern about peer review processes. Qualified reviewers who do not have conflicts of interest can be hard to find. Recourse is then often made to academic reviewers who appear marginally qualified. One solution is to make greater use of knowledgeable industry/ stakeholder reviewers.

Interdisciplinarity. Interdisciplinarity is considered vital in this field. There is a need for engineers to talk to geologists and vice versa. Some feel that multidisciplinary proposals are penalised, though this view is not universally shared. As well as collaboration across disciplines, the same set of skills can be applied across different areas of application. For example, there are skill requirements that cut across fossil fuel extraction, CCS, renewables (geothermal) and nuclear.

6.2 Long-term perspectives

As in other energy research areas, there is an argument in favour of longer-term funding perspectives, especially for field trials and pilot studies where it may take some years for investments to yield their full scientific benefit. At the same time, effective reporting and monitoring processes would be required to ensure that investments stay on track.

6.3 Data

The curation and accessibility of data underpins effective research in this area. BGS currently makes accessible data that is collected through public funding but not data collected with support from the private sector. The challenge of making more data available while respecting IP has been highlighted. The importance of establishing baseline geological and environmental data to support rigorous scientific investigations has been highlighted.

6.4 Infrastructure and facilities

Field trials. The vital importance of field trials across this research domain has been highlighted. These need to be large-scale and supported over the long-term by the nature of the geological processes involved. Pilot studies, exploratory boreholes and the more effective use of existing boreholes, e.g. those used for oil and gas or mineral deposits, are required. The latter can be achieved by 'piggy-backing' on existing activities. Establishing the right level and scale of monitoring is essential. Innovation in monitoring techniques would help greatly. Information about the location of CO_2 within storage sites is also needed.

Testing facilities. Access to shared infrastructure and facilities would be widely welcomed. These could be tied to research and training groups. However, these would require trust, knowledge transfer and connectivity across the innovation chain. The notion of a National Test Centre (for rapid testing and prototyping) appeals to some parts of the research community.

Experimental facilities. Large facilities such as the Diamond light source and the Isis neutron beams continue to be important in this field.

Computational facilities. New predictive models and modelling tools need to be verified to enable geological predictions up to 10,000 years out.

7. Training

General. UK MSc and PhD programmes are world leading and the research councils should advertise this to the UK government. Nevertheless, there is a shortfall of science and engineering graduates relative to UK needs. 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. The research councils need to be able to shape capabilities and they have been reasonably successful in certain areas, e.g. CCS and conventional generation. Some believe that the appropriate trade-off between research and training has not yet been made. Maintaining core capacity in the fossil fuel and CCS area will bring benefits both in the short- and long-term. Capabilities developed in the CCS domain should be transferrable into the fossil fuel domain and *vice versa* and investments should be robust against a range of scenarios.

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

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

Understanding of policy/markets. There needs to be an improved understanding in academia of what skills are transferrable to industry. Industry struggles to get good people in sufficient volume with the 'right' background. More multidisciplinary awareness would be useful in this respect. For example, we need to train generalists who are 'socially' aware of public perception issues as well as specialists.

Masters training. There is some support, notably from industry in this sector, for the research councils supporting Masters level training. We need to ensure that the world-leading standard of our Masters courses are recognised. In general, a range of academic qualifications, e.g. Masters and Engineering Doctorates, not just conventional PhDs, is needed.

Professional development and career progression. There is a problem of transition from post-doctoral positions through to permanent academic posts. The career path for post docs needs improved. To have an appropriately skilled workforce we need not only academic skills (e.g. theory of application, PhDs) but also professional/industry skills (e.g. process of application). Sandwich training has a role to play.

8. Making connections

8.1 Connections across research areas

Aspects of fossil fuel and CCS research are strongly related to other areas of energy research in terms in terms of the underpinning science. Research council investments relating to training or the enhancement of capabilities could usefully take account of these linkages in order to promote the transferability of research skills.

Table 6: Connections between Fossil Fuels and CCS and other research areas

Fossil fuels and CCS	Other energy research areas	Disciplinary linkages
• coal production • underground coal gasification • advanced oil and gas production • enhanced oil and gas production • unconventional oil and gas production • storage of gas and • carbon storage	• geothermal energy • uranium and thorium extraction and • geological storage of nuclear waste	• geological sciences
• coal combustion • oil and gas combustion and • carbon capture	• biomass heat and electricity	• combustion and conversion sciences and • mechanical and chemical engineering
• refining/transport/storage of oil and gas	• other biomass-derived fuels and • transport biofuels	• chemical engineering
• CCS, BECCS	• energy systems research	• economics, engineering

8.2 Linkages outside the Research Council sphere

Wider innovation support. There is a very widespread view that there needs to be a more joined-up approach and more coherence across the innovation landscape, perhaps informed by a 'value-chain' approach. The research councils, Technology Strategy Board (TSB), ETI, DECC, Department of Environment, Food and Rural Affairs (Defra) and industry need to act in concert. Establishing who funds what is essential. As noted above, since so much fossil fuel R&D is conducted in the private sector, the main role of public sector R&D is to develop generic knowledge regarding resources and their characterisation, develop and advance pre-commercial technologies, respond to basic science and engineering problems suggested by technology demonstration and deployment and support the regulation of the sector. Joint funding support from the research councils and other innovation bodies would be appropriate in addressing some of these research challenges. There is scepticism about the utility of the technology readiness level (TRL) concept in establishing research council priorities as innovation is not linear and flexible portfolios need to be maintained. There is some disagreement as to whether academic researchers have any role to play in developing standards, with industry generally more sceptical.

Policy. There is concern that there has been a lack of national leadership in relationship to oil and gas research which has largely been left to industry. This contrasts with the approach of the US DOE. Many view positively the US DOE model of a strategic/proactive approach coupled with a willingness to take risks with high cost/high value investments. Policy clarity about the priority attached to environmental impact studies would also be helpful.

Industry. Academic linkages with industry, in terms of both thinking and doing, are considered very important. Industry works mainly through incremental improvements and that needs to be taken into account as the research councils implement their strategies. Industry needs help in identifying and accessing the academic skills base.

Knowledge exchange. Establishing formal knowledge exchange arrangements is important.

8.3 International working

It was acknowledged in the Energy Strategy Fellowship expert workshop that international collaborations had a vital role to play in this field but this line of thinking was not well developed by participants. The UK has strengths in fields such as oil and gas which provide the basis for centres of global excellence. In other areas, notably geothermal, CBM and UGC the UK would be better placed relying on imported technology. In emerging areas such as CCS, where major commitments are needed to establish critical mass, the UK should pursue opportunities for international collaboration through EU **Horizon 2020** and bilateral initiatives with other leading countries such as the US and China. This collaboration will be fruitful only if current strong domestic capabilities are maintained.

8.4 Public engagement

In this field, understanding public perceptions and the degree of acceptance of new technologies is essential. The research councils could do more in terms of public engagement, for example through reach-out events to schools.

8.5 Other issues

Policy clarity. In this, as in most other areas of energy research, clarity about the direction of energy policy and a consistent vision of the future coupled with a sustained long-term funding structure would greatly help with research planning and encouraging younger researchers into the field. For example, the best students will not be attracted if there is continuing uncertainty about CCS deployment.

Strategic roadmapping. Commonly agreed frameworks and the development of portfolios of research activity that can be adapted in the light of changing priorities and new knowledge are needed. Strategic roadmaps may be helpful for prioritising and clarifying research needs but need to be adaptable to take account of changed circumstances.

9. Conclusions and recommendations

The dominant role of fossils fuels in the UK and the global energy systems is likely to continue for some time. 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 the degree to which strong climate change policies are implemented. For example, fossil fuel use would need to contract significantly if the UNFCCC objective of keeping global temperature increases below 2°C above pre-industrial levels were to be realised. CCS technology can help to reconcile climate policy goals and the use of fossil fuels. The research councils should hedge against these uncertainties by investing both in research that will improve the extraction and use of fossil fuels and in research relating to CCS. The skills acquired though doctoral training either domain are likely to have wider application.

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. The UK's competences in relation to coal extraction and exploitation are believed to be weaker, as are those in relation to CBM, UGC and geothermal energy. 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).

Research priorities covered by this report fall into three broad categories: sub-surface energy extraction; 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 resources of conventional coal, oil and gas; 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 on gas-fired generation; 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, notably the issue of liability and risk sharing between government and operators. Understanding the impacts of novel methods of energy extraction and CCS on the environment and ecosystem services is another priority area.

Many of these research challenges are not unique to the UK. Given the large scale of the R&D activities required in the fossil fuel and CCS domain, challenges that are common across countries may best be pursued internationally rather than through the UK acting alone. Other research challenges, such as those relating to resource characterisation and regulatory design, are UK-specific. Much of the R&D in the fossil fuel area is of an applied nature relating to the improvement of mature technologies and techniques. Such R&D is generally conducted by private companies. The main role of public sector R&D is to develop generic knowledge regarding resources and their characterisation, develop and advance pre-commercial technologies, respond to basic science and engineering problems suggested by technology demonstration and deployment and support the regulation of the sector.

Further development of high-level research challenges is needed to establish concrete research plans. Given the deep uncertainties about energy futures, the development of portfolios of research activity that can be adapted in the light of changing priorities and new knowledge would be advisable.

There are several ways in which research outcomes could be enhanced in this area: achieving critical mass through large-scale consortia and programmes; and better cross-Council working, including jointly funded projects, particularly those linking NERC and ESPRC. The need to link engineers and geologists is particularly important.

As in some other areas of energy research, there is an arguable scientific case for longer-term funding support as investments in field trials and pilot studies may take some years to yield their full scientific benefit. Linking research to field trials would be particularly beneficial. The fossil and CCS community also have concerns about data-sharing and access to experimental, testing and computational facilities.

The role of the research councils in providing qualified scientists and engineers is much valued, notably in industry where much of the relevant R&D takes place. As in all areas of energy research, there is opposition to the exclusive use of the CDT model in delivering PhD training. While the CDT model is a good one, it is believed that it has led to a big gap in the supply of trained people. A system where CDTs are complemented by project and discipline-based studentships would be more appropriate. Given uncertainties about the long-term future in this sector, PhD training should be designed so that the skills attained can remain relevant even if the industry changes radically. A balance between the acquisition of deep skills and wider transferrable skills is needed. There is some support, notably from industry, for the research councils to fund Masters level training.

There is a widespread view that the research councils, TSB, ETI, DECC, Defra and industry need to act in concert, clearly establishing who funds what. Joint action should focus on the appropriate tasks for public sector R&D, notably generating generic knowledge regarding resources and their characterisation and developing and advancing pre-commercial technologies. Common agreed frameworks combined with flexible and adaptable research portfolios are needed to support technological development. LCICG could help to facilitate in this area.

In this field, understanding public perceptions and the degree of acceptance of new technologies is essential. It is believed that the research councils could do more, though only a limited number of practical ideas (e.g. reach-out events in schools) has emerged.

In this, as in most other area of energy research, the community believes that clarity about the direction of energy policy and a consistent vision of the future coupled with a sustained long-term funding structure would greatly help with research planning and encouraging younger researchers into the field. However, the community needs to respond to continuing uncertainty by developing and pursuing flexible research portfolios.

Annex A: Research needs

A.1 Carbon capture, storage and utilisation

Power plants and CO_2 capture:

- Systems level assessment of power plant/capture systems
- Capital cost reduction and improved efficiency
- Energy penalty reduction
- Fuel flexibility
- Value engineering, scaling
- Potential for carbon negative biomass with CCS and
- Reducing impurity levels in CO_2 streams

Direct air capture

- No detail emerged from the consultative process

CO2 transport:

- Cost reduction for CO_2 transport without compromising health and safety
- Operability and flexibility, e.g. intermittent flow of CO_2
- Reuse of existing pipelines
- Non-pure CO_2 and linking mixed input streams (different sources, compositions and flow rates)
- Effect of small impurities from capture processes on storage/transport
- Scalability and understanding constraints (e.g. impurity levels)
- Materials and structural integrity to allow thinner and cheaper pipelines
- Damage mitigation, including how cracks become established and grow and the consequences of pipeline fracture
- The implications of moving to larger/more distributed networks (control constraints, operating parameters, flexibility)
- The 'right' level of system redundancy
- Development of international standards and guidance
- Science and engineering for metering that is 'good enough' for fiscal purposes

Carbon storage:

- Understanding flow in aquifers
- Main field (outwith well): understanding dissolution and reactivity of CO_2 and CO_2-enriched fluids, and their potential consequences
- Near field transient effects
- Understanding concepts for enhancing storage and trapping, e.g. water or CO_2 saturated water acting as a buffer
- Impact of impurities on reservoirs and reservoir injectivity
- CO_2 containment
- Leakage through legacy boreholes (containment integrity)
- Mechanical damage to natural seals
- Borehole integrity and engineering of boreholes.

A.2 Sub-surface activities

Hydraulic fracturing:

- Assessment methods for well integrity
- Understanding and modelling of growth of fractures
- Understanding the overburden
- Long term integrity of wells and cement when dealing with high pressure and temperatures
- Reducing the cost of analysis tools
- Options, such as better sensors, that would reduce the need for drilling and
- Assessing the potential use of old wells

Geothermal energy:

- Assessing permeability of rock in areas of abundant geothermal energy via 3D simulation
- Methods for improving permeability to increase flow
- Understand impacts on water quality
- Heat abstraction: how much heat can be sustainably extracted before there is a reduction in flow? Optimisation and planning
- Environmental impacts: subsidence, seismicity and water depletion
- Regulation of geothermal water extraction and licenses
- Heat networks and methods for harnessing geothermal energy for heat and electricity generation Use of existing void spaces (eg mines) to access low level geothermal heat?
- Improvements in heat exchange technologies

Energy Storage:

- Energy storage potential within fossil and CCS systems
- Gas storage and
- Compressed air storage

Methane hydrates:

- No detail emerged from the consultative process

Cross-cutting sub-surface research questions:

- Reactive fluid flow
- Imaging and remote sensing
- Understand earth materials properties in novel matrices
- Composition of produced gas/oil
- Long-term behaviour of well and facilities construction materials (steel/cement etc)
- Modelling at all scales from fundamental physics at the micro-scale to macro-scale
- CO_2 options linked with other uses of the subsurface and
- 'Knowledge based dynamic management' of sub-surface systems

A.3 Cross-cutting research questions

Systems approaches:

- Redefining the boundaries of engineering systems to recognise how primary energy transformation is linked to end use and the potential value of key innovations
- Managing the value propositions associated with technologies in order to gain competitive edge
- Incremental developments as well as step changes
- Heat utilisation

Impact studies and monitoring:

- Planning/policy/regulatory/legal issues nationally and internationally
- Water (use, supply, contamination – e.g. solvents for hydraulic fracturing)
- Seismicity
- Ecological impacts
- Need for baseline data and field studies
- Monitoring strategies for seismicity, air, geology etc
- Establishing the right level and scale of monitoring
- Innovation in monitoring techniques
- Health impacts
- Public perceptions of and attitudes to sub-surface activities
- Characterisation and communication of risks and hazards and
- Natural capital and valuation (monetary and non-monetary metrics)

Annex B: Process for developing the prospectus

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

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

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

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

Annex C: List of prospectus reports

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