Research Councils UK Energy Programme Strategy Fellowship

ENERGY RESEARCH AND TRAINING PROSPECTUS: REPORT NO 8

Bioenergy

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Prof Jim Skea
Dr Aidan Rhodes
Dr Matthew Hannon
Centre for Environmental Policy
Imperial College London
14 Princes Gardens
London SW7 1NA

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

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 needs*' 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 Jem Woods of Imperial College London. While the report draws on extensive consultations, the views expressed are those of the Fellowship team alone.

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Executive Summary

This report covers the **Bioenergy** area, which is more complex than those associated with other forms of renewable energy. Bioenergy is neither a technology nor a fuel; it describes a system comprising multiple supply chains covering crop production, harvesting, conversion, transport and use. Unlike most other forms of renewable energy which are restricted to electricity generation, bioenergy can be used for electricity generation, heat and transport. The final products associated with bioenergy can come in solid, liquid or gaseous forms. Bioenergy can be stored and traded, locally and internationally. Consequently, biomass power stations can be dispatched like fossil fuel plants and unlike intermittent renewables such as wind and solar. The UK imports bioenergy as well as relying on indigenous resources. Finally, biomass, the raw material feeding into bioenergy systems, has multiple uses. The most important are for food but biomass can also be used as a source of building or industrial materials.

There are multiple sustainability issues associated with bioenergy. These include direct and indirect competition for land ('food versus fuel'), the life cycle greenhouse gas (GHG) emissions associated with individual bioenergy chains, impacts on and management of water use and availability, and biodiversity impacts.

Bioenergy meets about 10% of world energy demand, most of it in the form of solid biomass. The role of bioenergy in future energy systems various widely across different energy outlooks and scenarios, both globally and at the UK level. One of the reasons is increasing concern about the life cycle GHG emissions associated with certain bioenergy chains and wider sustainability impacts. At the same time, there is a growing perception of an abundance of fossil fuel resources. It has been estimated that one fifth of global energy could be provided by biomass without damaging food production, though oil companies' estimates of the bioenergy contribution to global energy by 2040 are in the range 7-10%. In the UK, different scenarios envisage bioenergy meeting 5-25% of energy demand by 2040. Much of that wide variation is accounted for by differences in assumptions about the availability of, sourcing and technologies associated with imported biomass. The availability or otherwise of carbon capture and storage (CCS) is a key differentiator in terms of future markets for bioenergy. Without CCS, the most appropriate use of biomass would probably lie in transport fuels. With CCS, removing CO_2 from the atmosphere through bioenergy with CCS (BECCS) becomes an option. Given uncertainties, research, development and demonstration (RD&D) strategies should be designed to prepare for a wide range of futures for bioenergy.

The most important input to this report has been a two-day, facilitated expert workshop involving academics, researchers and other stakeholders held at Rothamsted Research on 14-15 May 2013. There is wide agreement that the UK has considerable scientific strengths relevant to bioenergy, especially in relation to crop breeding, genomics and growing biomass. There are also strengths in relation to biomass conversion. The bioenergy research community displays greater self-confidence about its capabilities than do most other UK energy research communities. The Biotechnology and Biological Sciences Research Council (BBSRC) and the Engineering and Physical Sciences Research Council (EPSRC) have made important investments supporting their respective communities. However, industrial capabilities are perceived to be weaker and improved collaboration along the innovation chain is deemed desirable.

'Bioenergy' is a system comprising many diverse supply chains and hence research needs are varied and complex. Research needs identified in this report range from fundamental to applied and fall into six main areas: fundamental research and novel solutions; applications and product improvement; risk, resilience and climate change; bioenergy systems and supply chains; sustainability; and social

acceptability. These reflect research needs identified in a range of roadmapping exercises conducted in the UK and internationally.

Fundamental research is needed to address the breakdown of lignocellulosic material in cells to underpin next generation biofuels with lower life cycle GHG emissions. Other lines of enquiry concern genetic manipulation to alter biomass composition, prospecting genetic diversity, novel chemistry for fuels and materials, synthetic biology, artificial photosynthesis and, more speculatively, bioluminescent lighting. The investigation of algal biomass, including cultivation and downstream processing, is another fundamental research opportunity.

In terms of application and product improvement, the focus needs to be on improving product quality and yields during conversion. A supply chain view is needed to ensure that feedstocks and conversion processes are well-matched. Selection of catalysts is a critical factor. Designing processes that can tolerate a range of feedstocks will encourage commercial application. Systems research, and research at the agronomic level, is also needed to understand how bioenergy cropping can best be integrated into existing landscapes and systems.

The need to build in resilience to climate change and other factors helps to define a number of research challenges. These include higher yields, lower water use, lower life cycle GHG emissions and better use of nitrogen, potassium and phosphates. Resilience to extreme weather and future climate change is also important. Designing crops suitable for cultivation on marginal land will help to minimise food versus fuel conflicts. Integrating of perennial cropping systems with annual cropping could ameliorate the impacts of climate-related flooding and drought.

A system-level view of bioenergy and bioenergy supply chains is needed. This includes whole system analysis, landscape perspectives, consideration of the most appropriate use of biomass for energy, integration of cultivated crops and processing techniques, the development of bio-refinery concepts and the utilisation of co-products. There is also a need to explore logistics along the supply chain. There needs to be research support for the development of standards to underpin commercialisation.

Sustainability throws up a wide range of research challenges but the emergence of new markets for biomass suppliers can also provide new market opportunities. A better understanding of life cycle GHG emissions and the environmental impact of land use change is critical. Exploring the viability of large-scale BECCS is part of the former challenge. Indirect land use change (ILUC) must be addressed. More specific topics include a better understanding of the UK natural resource base, competition for land use and impacts on biodiversity, water use, nutrient recycling and wider ecosystems services. Finally, a better understanding of public perception and the social acceptability of bioenergy cultivation and use is needed. This needs to be framed in terms of air quality, water quality, soil, aesthetics, landscape and biodiversity as well as local environmental impacts, e.g. lorry movements associated with biomass heat and power plants.

A number of steps could be taken to enhance research outcomes in the UK. Better linkages between funding agencies are a priority. The research communities supported by BBSRC and EPSRC operate rather separately and more coordination is needed to avoid gaps in the research agenda and link activities focused at different points in the supply chain. There is also a need for better coordination between the research councils and later stage energy innovation funding bodies. The establishment of the Technology Strategy Board (TSB)-BBSRC **Agri-tech** catalyst suggests a possible model.

There is a need to support more extensive, fully monitored field trials. Longer funding cycles may be needed, though these should be stage-gated to ensure that unproductive lines of research are discontinued. Mechanisms for curating data arising from field trials and other experiments could be improved so as to avoid re-inventing the wheel and to speed up commercialisation. Relevant data would cover: genomics; crop traits and physiology and crop improvement.

There is a perceived need to improve links between the research community on the one hand and industry and landowners on the other. Closer links would allow better access to land and would allow knowledge acquired from demonstration and applied research back to the research community.

As in other areas of energy research, there is a desire to see PhD studentships supported through large interdisciplinary programmes and projects as well as through Centres for Doctoral Training (CDTs).

Acronyms

AD	anaerobic digestion
ADAS	Agricultural Development Advisory Service (former name of consultancy company)
BBSRC	Biotechnology and Biological Sciences Research Council
BECCS	bioenergy with CCS
BioDME	biological dimethyl ether
BioSNG	biological synthetic natural gas
BIS	Department for Business, Innovation and Skills
BSBEC	BBSRC Sustainable Bioenergy Centre
BtL	biomass to liquids
CASE	Collaborative Awards in Science and Engineering
CCC	Committee on Climate Change
CCS	carbon capture and storage
CDT	Centre for Doctoral Training
CEH	Centre for Hydrology and Ecology (NERC)
CfD	contract for difference
CHP	combined heat and power
DECC	Department of Energy and Climate Change
DoE	Department of Energy (US)
EBTP	European Biofuels Technology Platform
EEA	European Environment Agency
EERA	European Energy Research Alliance
EII	European Industrial Initiative
EIT	European Institute for Innovation and Technology
EJ	exajoules
ELUM	Ecosystem Land-Use Modelling (ETI research project)
EPSRC	Engineering and Physical Sciences Research Council
ERA-NET	European Research Area Network
ESRC	Economic and Social Research Council
ETI	Energy Technologies Institute
FAME	fatty acid methyl ester
FAPESP	Fundação de Amparo à Pesquisa do Estado de São Paulo
FiT	feed-in tariff
FP7	EU Framework RTD Programme 7 2008-13
GHG	greenhouse gas
GTL	Genomes To Life (DoE program)
ha	hectare
HVO	hydrotreated vegetable oil

IA	Implementing Agreement (IEA technology cooperation)
IBERS	Institute of Biological, Environmental and Rural Sciences (Aberystwyth University)
IEA	International Energy Agency
ILUC	indirect land use change
KIC	Knowledge and Innovation Community
LCA	life cycle assessment
LCICG	Low Carbon Innovation Coordination Group
LUC	land use change
NCIL	no clear international lead
NERC	Natural Environment Research Council
NICE	National Institute for Health and Care Excellence
NIBB	Networks in Industrial Biotechnology and Bioenergy (BBSRC)
OECD	Organisation for Economic Cooperation and Development
PI	Principal Investigator
PJ	petajoules
RCEP	RCUK Energy Programme
RCUK	Research Councils UK
R&D	research and development
RD&D	research, development and demonstration
RED	Renewable Energy Directive (EU)
RO	Renewables Obligation
RTD	research and technology development
SET	SET plan – Strategic Energy Technology Plan (EU)
SME	small-to-medium sized enterprise
STFC	Science and Technology Facilities Council
TINA	Technology Innovation Needs Assessment
TRL	technology readiness level
TSB	Technology Strategy Board
UKERC	UK Energy Research Centre
UNFCCC	UN Framework Convention on Climate Change
UNICAMP	Universidade Estadual de Campinas

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 bioenergy. 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 Coordination 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 Rothamsted Research on 14-15 May 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 Biotechnology and Biological Sciences Research Council (BBSRC) 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 covers Area III.4, **Bioenergy**, covering the production of transport biofuels and other biomass-derived fuels, applications for heat and electricity, energy crops and research on bio-energy production potential and land-use effects.

The **Bioenergy** area is more complex than those associated with other forms of renewable energy. Bioenergy is neither a technology nor a fuel; it describes a system comprising of multiple supply chains covering crop production, harvesting, conversion, transport and use (Figure 1). Unlike most other forms of renewable energy which are restricted to electricity generation, bioenergy can be used for electricity generation, heat and transport. The final products associated with bioenergy can come in solid, liquid or gaseous form. These are referred to as solid biomass, biofuels and biogases respectively in this report. Bioenergy can be stored and traded, locally and internationally. Consequently, biomass power stations can be dispatched like fossil fuel plants and unlike intermittent renewables such as wind and solar. The UK can import bioenergy as well as relying on indigenous

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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

resources. Finally, biomass, the raw material feeding into bioenergy systems, has multiple uses. The most important are for food but it biomass can also be used as a source of building or industrial materials.

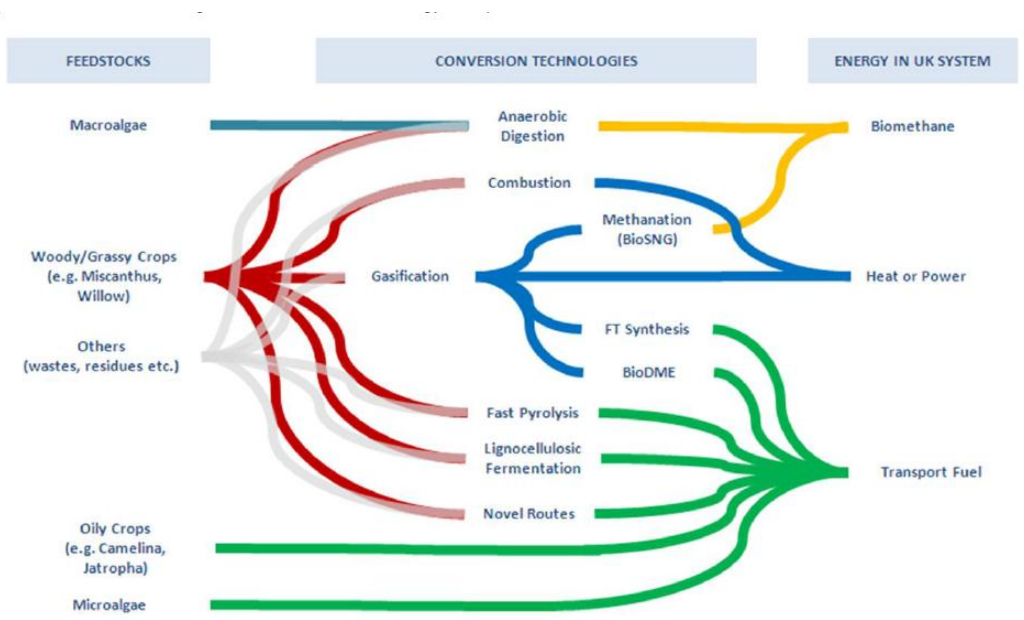

Figure 1: Flow chart for selected bioenergy chains
Source: LCICG[5]

There are multiple sustainability issues associated with bioenergy. These include direct and indirect competition for land ('food versus fuel'), the life cycle greenhouse gas (GHG) emissions associated with individual bioenergy chains, impacts on water use and availability, and biodiversity impacts.

The research needs associated with bioenergy are therefore wide-ranging and require inputs from many disciplines. The IEA nomenclature is biased heavily towards bioenergy conversion and application (engineering and the physical sciences) with little detail on crop improvement and land use effects. This report, and the associated expert workshop, deal with the wider bioenergy research agenda.

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 bioenergy 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 Rothamsted workshop. Section 5 sets out high-level research challenges in the six areas upon which the workshop focused. Annex A expands on 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 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. Section 9 summarises conclusions and recommendations.

[5] Low Carbon Innovation Coordination Group, **Technology Innovation Needs Assessment (TINA): Bioenergy Summary report**, September 2012. http://www.lowcarboninnovation.co.uk/document.php?o=9

2. Current and future role of bioenergy

2.1 Global perspectives

Bioenergy contributes about 10% of global primary supply or 55 exajoules (EJ), 60% of it in the form of solid biomass used in developing countries. Figure 2 shows that the use of solid biomass grew at 2.6% per year 1990-2011with the fastest growth in Africa (5.1%). The use of 'modern' solid biomass in Organisation for Economic Cooperation and Development (OECD) countries has grown at 2.0% per year and meets 5% of energy demand. Asia and Africa still dominate global consumption of solid biomass for energy, largely in traditional forms.

Consumption of liquid biofuels (Figure 3) is an order of magnitude less than that of solid biomass. The use of liquid biofuels for transport has expanded very rapidly in the last ten years, mainly in North America but also in Europe and Latin America. Brazil has led the development of ethanol from biomass crops (sugar cane) since the 1970s and there has been a second round of expansion since the mid-2000s enabled by the marketing by several major manufacturers of flexible fuel vehicles which can run on any blend of ethanol and gasoline. US production of ethanol, from corn, overtook Brazilian production in 2005. The development of biofuels in the EU has been driven by the Renewable Energy and Fuel Quality Directives. The former established mandatory national targets leading to a 10% share of energy from renewable sources in transport by 2020.[6] The latter requires life cycle GHG emissions from fuel and energy supplied to fall by at least 6% by 2020, compared to average life cycle GHG emissions per unit of energy from fossil fuels in 2010.[7]

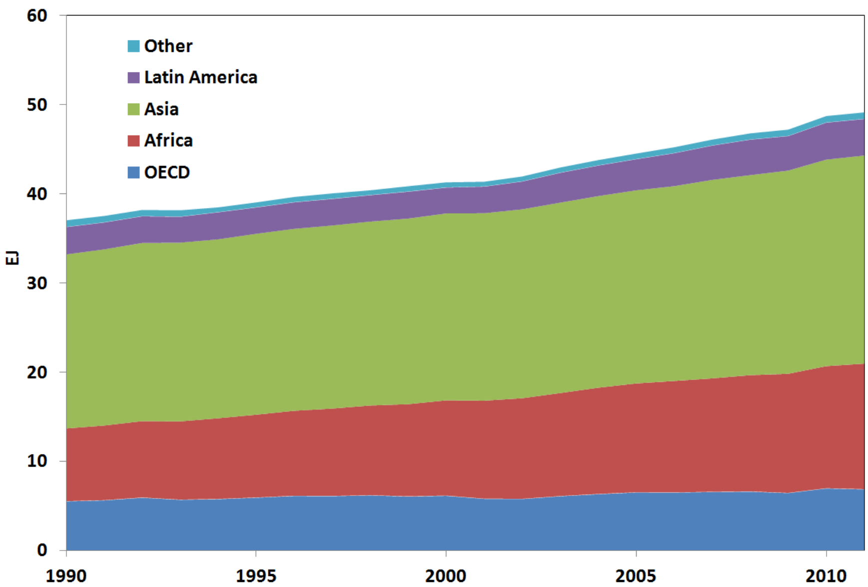

Figure 2: Global production of solid biomass for energy
Source: IEA, 2013[8]

6 European Commission, Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources, **Official Journal of the European Union**, L140/16, 5 June 2009. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=Oj:L:2009:140:0016:0062:en:PDF

7 European Commission, DIRECTIVE 2009/30/EC of the European Parliament and of the Council of 23 April 2009 as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions, **Official Journal of the European Union**, L140/88, 5 June 2009. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0088:0113:EN:PDF

8 International Energy Agency (2013): **Renewables Information** (Edition: 2013). Mimas, University of Manchester. DOI: http://dx.doi.org/10.5257/iea/ri/2013

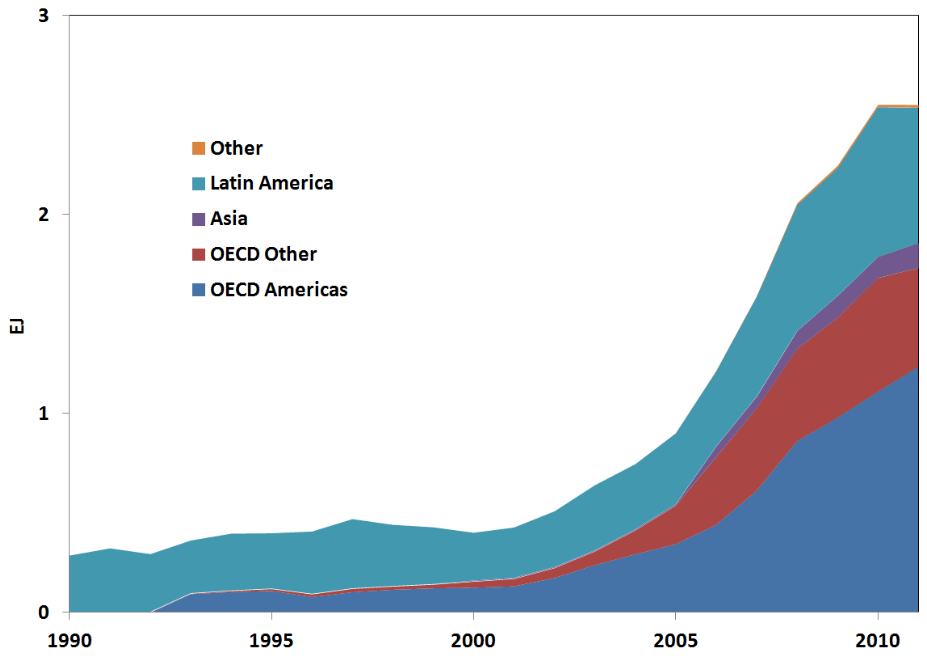

Figure 3: Global production of liquid biofuels
Source: IEA, 2013

The use of biogases (Figure 4) is lower still. Landfill gas accounted for the bulk of production till 2005, but this has been exceeded by the processing of sewage sludge, animal slurries and agri-food wastes. OECD countries and China account for the bulk of production.

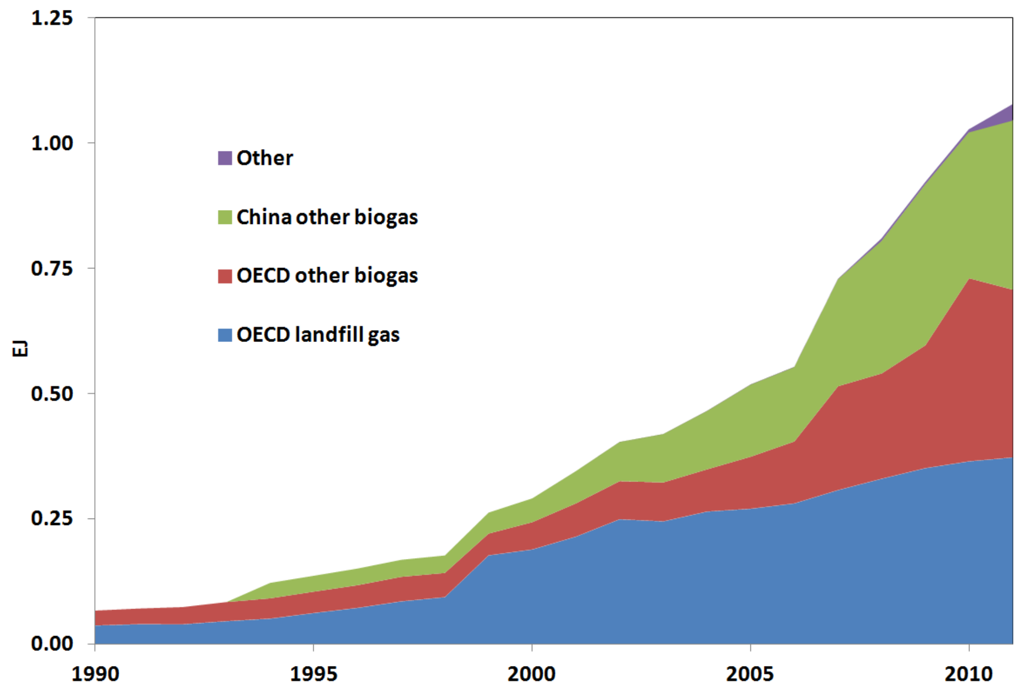

Figure 4: Global production of biogases
Source: IEA, 2013
Note: 'Other biogas' covers fermentation of sewage sludge, animal slurries and agro-food waste

The wider sustainability implications of bioenergy development have received widespread attention in recent years. Some have pointed out fundamental problems with the attribution of GHG emissions to countries under UN Framework Convention on Climate Change (UNFCCC) accounting rules[9] and have argued that there are fundamental problems with bioenergy sustainability, mainly in respect of indirect land use change (ILUC).[10] The European Environment Agency (EEA) acknowledges that renewable energy technologies can allow society to meet its energy needs at a lower environmental cost but is concerned that wider environmental impacts are not built into EU bioenergy policy and that, if not managed within a resource efficiency framework, some bioenergy pathways could increase GHG emissions.[11] On the other hand, the emergence of new markets for biomass suppliers can stimulate the production base and provide new market opportunities.[12] Figure 5 shows the range of lifecycle GHG emissions associated with different bioenergy chains compared to the relevant fossil fuel alternative. In some cases, notably corn ethanol, life cycle emissions could be higher than those of the fossil fuel alternative. Figure 5 does not take any account of land use change, whether direct or indirect.

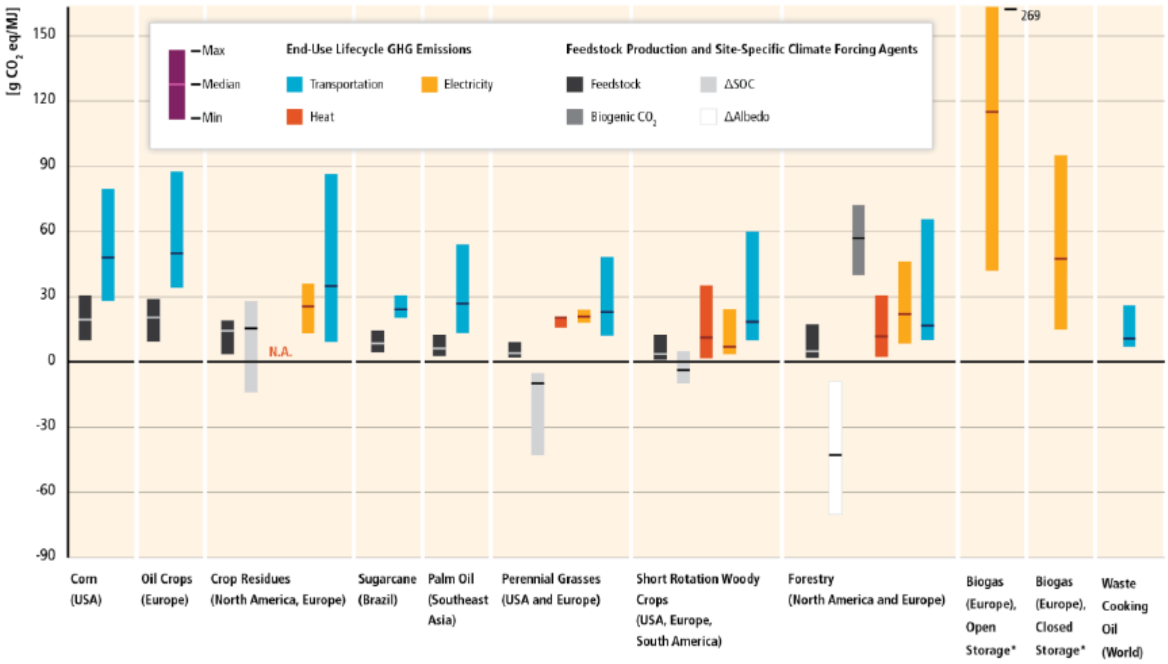

Figure 5: GHG emissions from major bioenergy product systems
Source: IPCC, Bioenergy Appendix to Chapter 11, AFOLU, Fifth Assessment Report, 2014

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9 Searchinger T. et al. (2009), 'Fixing a Critical Climate Accounting Error, Supporting Information, **Science** 326:527-528

10 ILUC refer to the process by which food production displaced by bioenergy crops is displaced may then take place on undeveloped land with negative indirect effects on GHG emissions

11 European Environment Agency, **EU bioenergy potential from a resource efficiency perspective**, EEA Report No 6/2013, ISSN 1725-9177. http://www.eea.europa.eu/publications/eu-bioenergy-potential/at_download/file

12 Smith, P., Bustamante, M. et al. (2014). Bioenergy: Climate effects, mitigation options, potential and sustainability implications. Appendix to Chapter 11, Agriculture, Forestriuty and Other Land Use (AFOLU). In: Edenhofer, O. et al. **Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change**, Cambridge University Press, Cambridge, United Kingdom and New York, NY, US

The UK Energy Research Centre (UKERC) produced a comprehensive report on the global potential for bioenergy in the light of sustainability constraints in 2011.[13] The report reviewed more than 90 global studies and concluded that up to one fifth of global energy could be provided by biomass without damaging food production (Figure 6). Figure 6 includes the use of agricultural residues (about 30 EJ) that are excluded from most other studies. The report identified the conditions under which higher levels of production might be feasible. The main factors, about which different assumptions are made in different studies, are population, diet, land use and, especially, the speed with which productivity improvements in food and energy crop production can be rolled out.

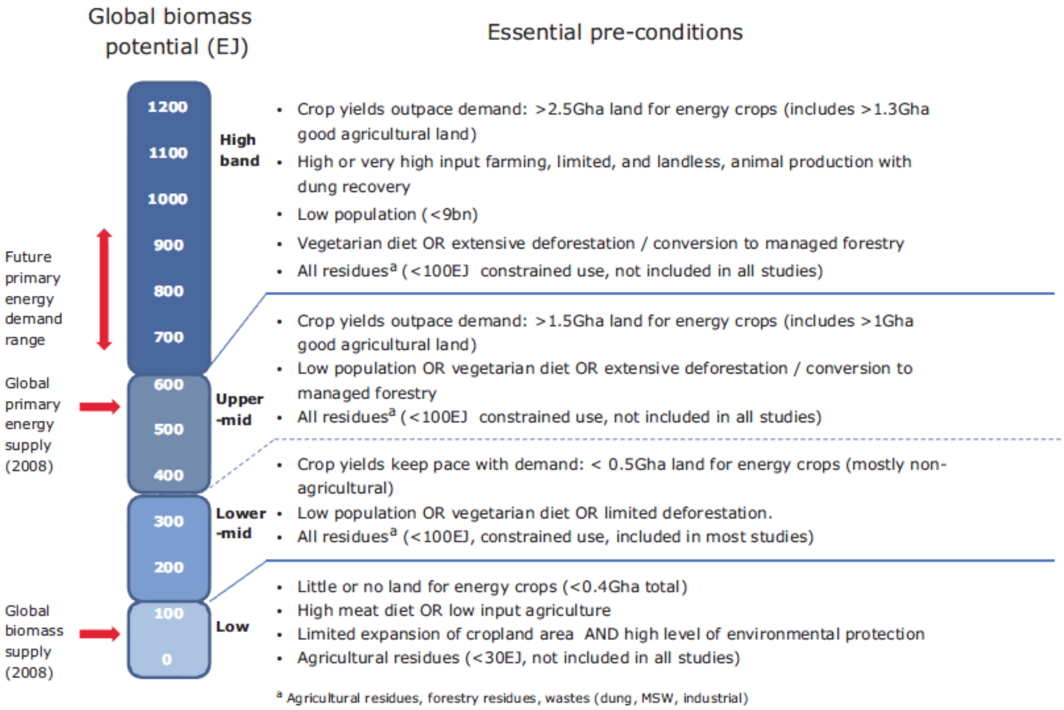

Figure 6: Common assumptions for high, medium and low biomass potential estimates
Source: Slade et al, 2011[14]

Global projections and scenarios concerning bioenergy are particularly diverse. Table 1 compares recent projections out to 2040 from IEA, Shell, BP and ExxonMobil.[15] None of the oil company studies envisage bioenergy production (excluding agricultural residues) meeting more than 10% of global primary energy demand. The Exxon outlook and one of the Shell scenarios (Oceans) foresee the contribution to primary energy demand falling to 7% from today's level. The IEA on the other hand foresees bioenergy meeting 20% of global energy demand by2040 under the 2 degrees scenario which is consistent with meeting the UNFCCC objective of preventing global temperature form rising more than 2°C above pre-industrial levels. Allowing for agricultural residues, this is higher than the level of sustainable supply identified by UKERC. In the IEA 2 degrees scenario there is some use of

13 Raphael Slade, Robert Saunders, Robert Gross, Ausilio Bauen. **Energy from biomass: the size of the global resource** (2011). Imperial College Centre for Energy Policy and Technology and UK Energy Research Centre, London. ISBN: 1 903144 108, http://www.ukerc.ac.uk/support/tiki-download_file.php?fileId=2095

14 Raphael Slade, Robert Saunders, Robert Gross, Ausilio Bauen. **Energy from biomass: the size of the global resource** (2011). Imperial College Centre for Energy Policy and Technology and UK Energy Research Centre, London. ISBN: 1 903144 108, http://www.ukerc.ac.uk/support/tiki-download_file.php?fileId=2095

15 These are difficult to compare because the coverage of bioenergy varies across the different scenario exercises.

solid biomass with carbon capture and storage (BECCS) resulting in negative emissions. Least cost models of global energy that are constrained to meet the 2°C goal tend to select BECCS.[16]

The pattern is similar for liquid biofuels for transport. BP, with the lowest estimate, foresees a doubling of production by 2040 mainly in the core markets of Brazil and the US. The IEA 2 degrees scenario foresees demand increasing by a factor of seven. Shell and the other IEA scenarios foresee demand increasing by a factor three-four. Oil companies' expectations about biofuels have declined over recent round of forecasts, partly because of sustainability issues and partly because of the abundance of fossil fuel resources.[17]

Table 1: Projected global bioenergy supply in 2040 (EJ)[1]

	2010	2040						
		Shell		IEA			BP[2]	Exxon
		Mountains	Oceans	2 degrees	4 degrees	6 degrees		
Traditional biomass	33.2	39.9	24.2					
Solid biomass/waste	17.1	16.3	15.5					
Biofuels	2.5	10.0	7.2	18.7[3]	10.5[3]	7.6[3]	5.6	
Biogases	1.3	18.2	20.4					
Total	54.1	84.4	67.3	131.0	107.1	59.3		52.1
% primary energy	10.1%	10.3%	7.9%	20.6%	14.0%	10.4%		7.7%

Source: IEA (2012), Shell (2013), BP (2014); Exxon (2014)
Notes: 1) excludes agricultural residues; 2) extrapolated form 2035; 3) inferred from bioenergy use in transport

2.2 UK perspectives

The UK is required to meet 15% of its energy requirements from renewable energy by 2020 under the EU Renewable Energy Directive (RED). Starting from a baseline of 2.4% in 2008, this requires the UK to make rapid progress from a very low baseline. Table 2 shows that bioenergy could contribute up to 50% of the RED target by 2020 and up to one third of renewable electricity. Since the first Renewable Energy Roadmap was published in 2011,[18] steps have been taken to limit support and ambitions for bioenergy to ensure that genuine GHG emission reductions are achieved and that it is sourced from land that is managed sustainably. There is a limit of 400MW of on total new build biomass electricity and support levels under the Renewable Obligation (RO) and feed-in tariffs (FiTs) through contracts for difference (CfD) have been cut back.[19]

Figure 7 shows how the current use of bioenergy is split between electricity, heat and transport. Bioenergy for electricity dominates and has been expanding most rapidly (Figure 8). Landfill gas and energy-from-waste currently accounts for most electricity from bioenergy but plant biomass (including

[16] IPCC, **Summary for Policymakers, IPCC WG-III – Mitigation of Climate Change, Fifth Assessment Report**, 2014

[17] Jim Skea, Aidan Rhodes and Matthew Hannon, **Energy Research and Training Prospectus: Report No 5: Fossil Fuels and Carbon Capture and Storage**, RCUK Energy Strategy Fellowship. January 2014. https://workspace.imperial.ac.uk/rcukenergystrategy/Public/reports/Final%20Reports/RCUK%20ESF%20prospectus%20-%20Fossil%20fuels%20and%20CCS.pdf

[18] DECC, **UK Renewable Energy Roadmap**, 2011. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48128/2167-uk-renewable-energy-roadmap.pdf

[19] DECC, **Renewable Energy Roadmap: 2013 Update**. https://www.gov.uk/government/publications/uk-renewable-energy-roadmap-second-update

imported wood chips and pellets) has expanded most quickly since 2010. Figure 9 shows that a number of biomass electricity projects are still in the pipeline.

Table 2: Technology breakdown for central view of deployment in 2020 (TWh)

Onshore wind	24-32
Offshore wind	33-58
Biomass electricity	**32-50**
Marine	1
Biomass heat (non-domestic)	**36-50**
Heat pumps (non-domestic)	16-22
Renewable transport	**Up to 48**
Others (including hydro, geothermal, solar and domestic heat)	14
Estimated 15% target	234

Source: DECC, 2011

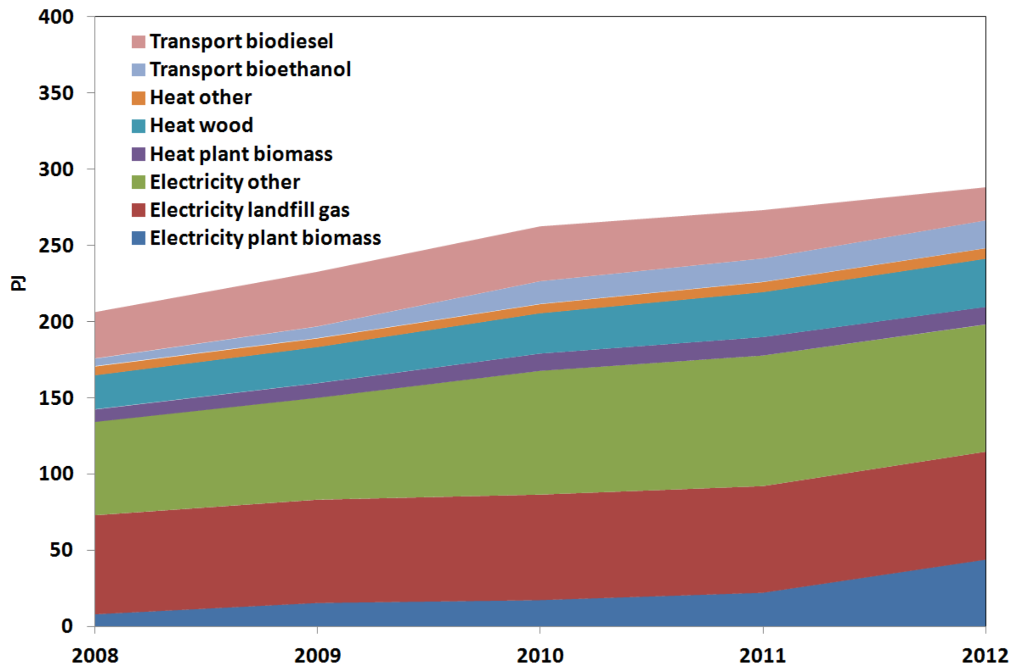

Figure 7: UK Bioenergy use 2008-12
Source: DECC (2013)

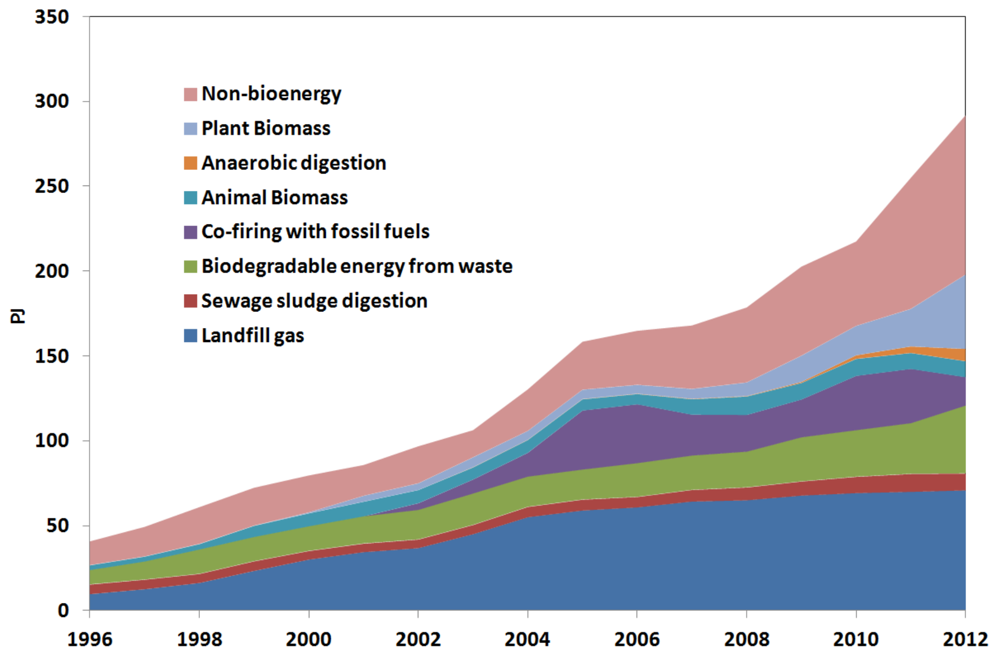

Figure 8: Bioenergy for electricity generation
Source: DECC (2013)[20]

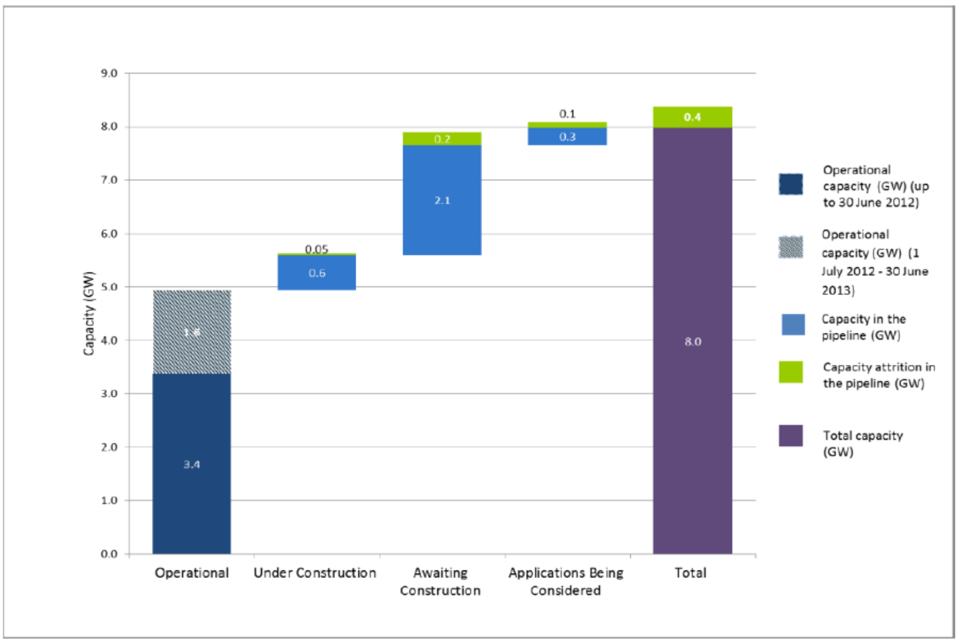

Figure 9: Capacity of biomass electricity projects that are operational and in the pipeline[21]
Source: DECC (2013)

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20 Department of Energy and Climate Change, **Digest of UK Energy Statistics**, Chapter 6: Renewable sources of energy, 2013. https://www.gov.uk/government/publications/renewable-sources-of-energy-chapter-6-digest-of-united-kingdom-energy-statistics-dukes

21 DECC, **Renewable Energy Roadmap Update**, 2013. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/255182/UK_Renewable_Energy_Roadmap_-_5_November_-_FINAL_DOCUMENT_FOR_PUBLICATIO___.pdf

Longer-term prospects for bioenergy in the UK are, as at the global level, highly uncertain. In developing its 2012 **Bioenergy Strategy**,[22] the UK Department of Energy and Climate Change (DECC) developed a number of scenarios for bioenergy supply (imports plus indigenous) available to the UK using a specially constructed 'appropriate use of bioenergy' model which took account of UK energy system developments (e.g. economic growth, prices of fossil fuels) and sustainability constraints.

The results of the medium feedstock availability scenario are shown in Figure 10. Biomass demand peaks at around 400 TWh (1400 petajoules (PJ) or 18% of 2012 primary energy demand) in 2040. Bioenergy use for electricity and heat peaks in 2020, the deadline for compliance with RED. In the period 2025-45, the bulk of bioenergy goes into liquid biofuels before being replaced by hydrogen produced from biomass.

Figures 11 and 12 contrasts the levels of biomass deployment in an ambitious supply scenario and under a highly restrictive sustainability standard. Under the ambitious supply scenario, demand peaks at 550 TWh (2,000 PJ or 25% of 2012 demand) in 2045. In the restrictive scenario, demand plateaus at around 175 TWh (630 PJ or 8% of 2012 demand) in the 2020s before falling from 2030 onwards. Figures 11 and 12 distinguish between indigenous production, imports and different biomass products. The biggest factor distinguishing the scenarios is the availability of imports of woody biomass which is heavily influenced by assumptions about sustainability standards. The use of UK forestry products and residues also distinguished the scenarios. The use of waste is robust across the different scenarios.

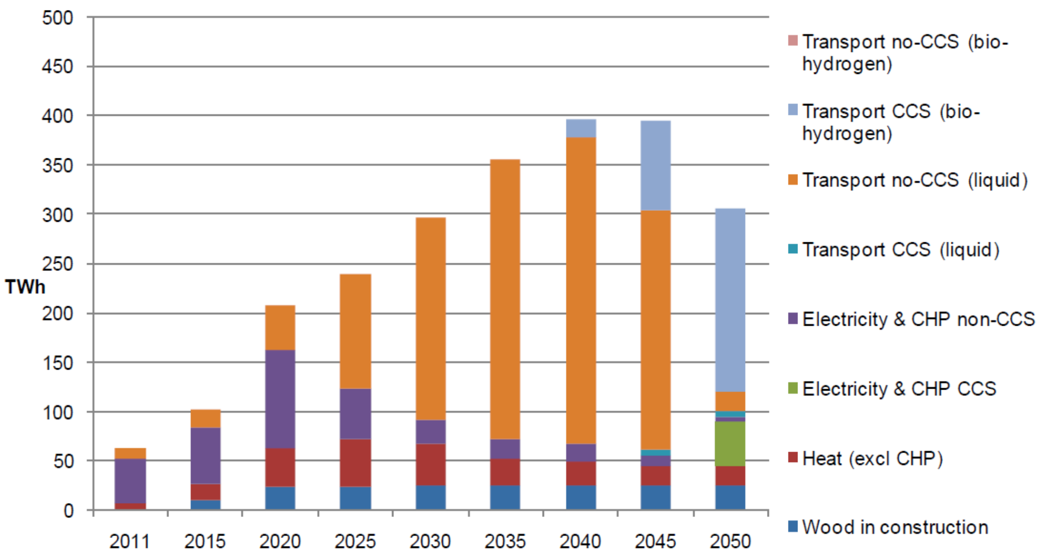

Figure 10: Biomass deployment for primary energy under medium feedstock availability scenario
Source: DECC (2012) [23]

[22] Department of Energy and Climate Change, **Bioenergy Strategy**, April 2012. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48337/5142-bioenergy-strategy-.pdf

[23] Department of Energy and Climate Change, Bioenergy Strategy Analytical Annex, URN: 12D/078, April 2012. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48338/5136-bioenergy-strategy-analytical-annex.pdf

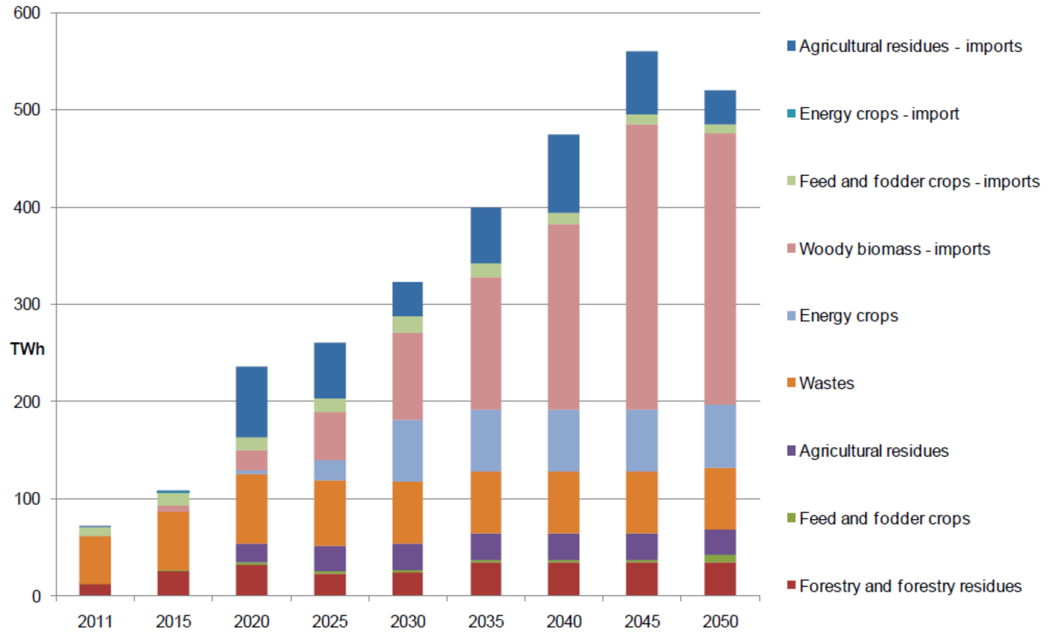

Figure 11: Biomass deployment by product under ambitious supply scenario
Source: DECC (2012)

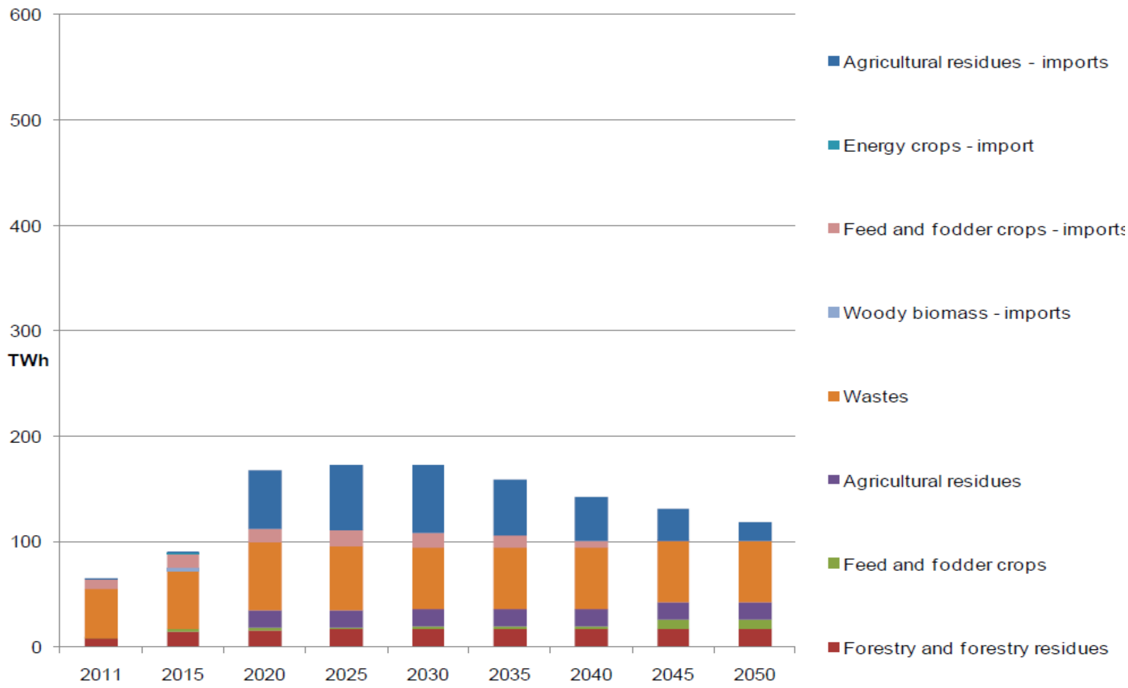

Figure 12: Biomass deployment by product under highly restrictive sustainability standard
Source: DECC (2012)

Each of the **Bioenergy Strategy** scenarios assumes that the UK's target of reducing GHG emissions by 80% by 2050 is achieved. This is not in line with the scenarios developed by fossil fuel producers which were presented in section 2.1. These envisage global GHG emissions continuing to rise. UKERC recently used the MARKAL model to develop a series of scenarios, some of which allowed for the 2050 target not being met. Table 3 compares bioenergy demand in 2040 in a **Reference** scenario with that in a **Low Carbon** scenario which did meet the target. Bioenergy meets only 4-5% of primary energy demand and transport fuel demand in the **reference** scenario, rising to 11.5% of primary energy demand and 31.0% of transport energy demand in the **Low Carbon** scenario. In the latter scenarios, most transport fuel is in the form of ethanol for light duty vehicles.

Table 3: Bioenergy in 2040 in the updated UKERC 2050 scenarios (PJ)

	Reference	Low Carbon
Bioenergy/waste	367	857
Total primary energy	8416	7455
% of total primary energy	4.4%	11.5%
Transport bioenergy	65.5	407.3
Total transport energy	1381	1315
% of transport energy	4.7%	31.0%

Source: Ekins et al., 2013[24]

Note: the **Reference** scenario is the REF-P2 scenario which removes the carbon price floor.

2.3 Bioenergy goals and expectations

The previous sections have shown markets for bioenergy ranging from 8% to 21% of primary energy demand at the global level and 5-25% in the UK. This very wide range of possibilities suggests the need for bioenergy to play a strong role in public sector energy R&D portfolios. However, at the same time, a degree of caution is needed in case market prospects turn out to be more limited. The fact that the sustainability of different bioenergy chains could have a major impact on deployment suggests an obvious need for research in that area.

3. 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 carbon capture and storage (CCS) as well as other energy areas;[25] b) subjective judgments of UK research capability levels made at the expert workshop; and c) peer-reviewed assessments of UK R&D capabilities documented through the UKERC Energy Research Atlas 'landscape' documents.[26] Although the UK plays a relatively small role in global bioenergy markets, it is perceived to play a disproportionately large role in terms of opinion-forming within the wider international bioenergy community.

[24] Ekins, Keppo, Skea, Strachan, Usher, Anandarajah, **Comparing Low-Carbon, Resilient Scenarios**, UKERC Research Report RR/ESY/2013/001, February 2013. http://www.ukerc.ac.uk/support/tiki-download_file.php?fileId=2976.

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

[26] http://ukerc.rl.ac.uk/ERL001.html

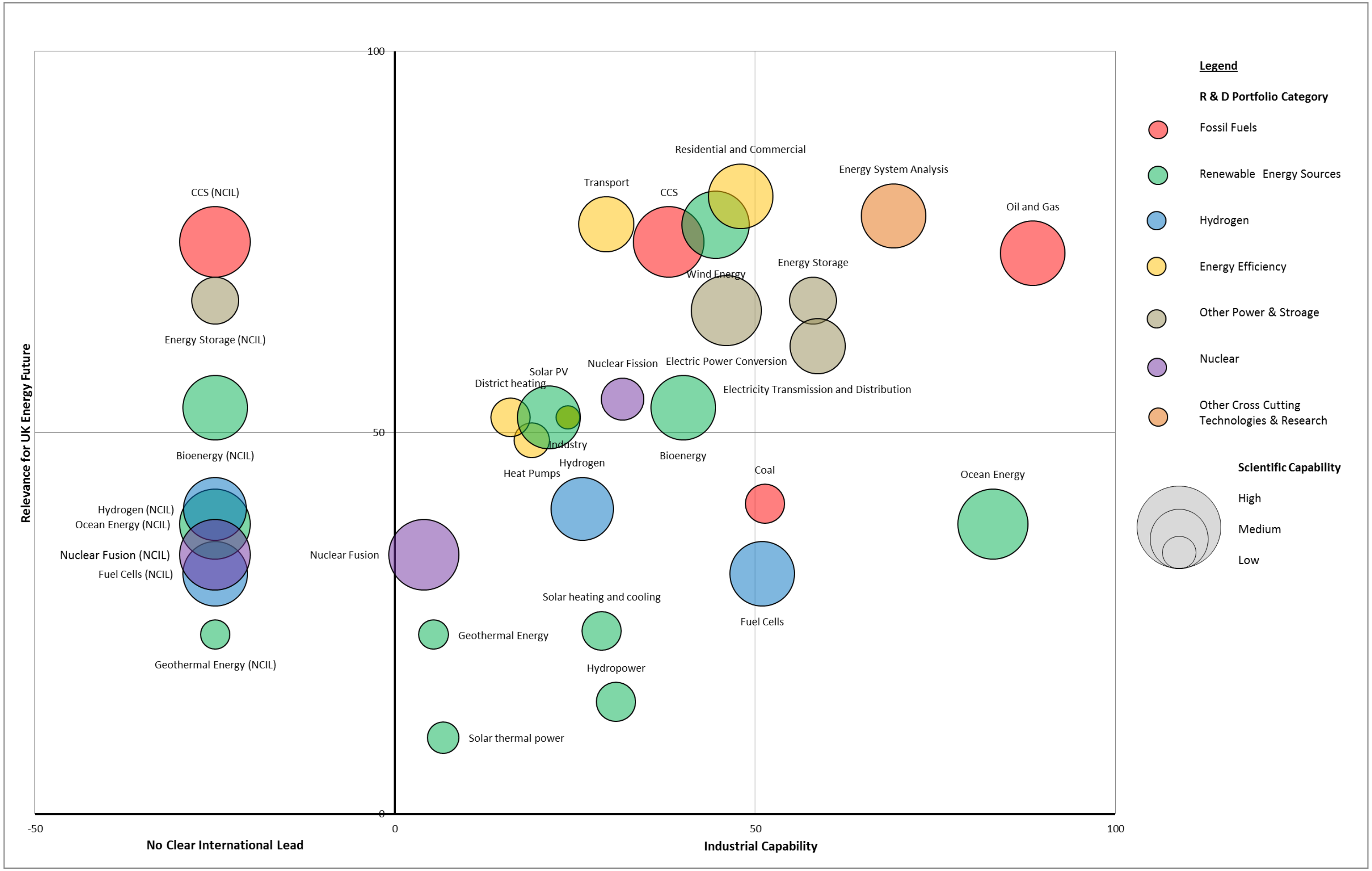

Figure 13: UK industrial and scientific capabilities and their relevance to future energy

3.2 Strategic Workshop

Figure 13 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 circles 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 where it is thought that one has yet to be established.

Participants judged the UK to be scientifically strong in relation to bioenergy and for bioenergy to have a moderate relevance for the UK's energy future. Some participants thought that the UK's industrial capabilities were on the low side; others thought that no clear international lead had yet been established. Given the diverse nature of bioenergy systems and technologies, divergences of view are not unexpected.

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 equipped in terms of research capabilities for tackling future challenges in the bioenergy field. The average score given by the group was 6.3 +/- 1.3. This represents a very high set of scores with most tightly clustered around 6 and one participant awarding the maximum 10 points. No-one assigned a low score to UK capabilities. The comments converged even more tightly than the quantitative scores (Table 4). A very strong theme emerging from the comments is the relative strength of the UK's fundamental science in the bioenergy field, coupled with perceived weaknesses in commercialisation and application. Fundamental plant and crop science was seen to be very strong but there were weaknesses in terms of harvesting, due to there being no industry to encourage it.

3.4 UK Research Landscape

The UKERC Research Landscape document on bioenergy has not been revised since 2009 but broadly confirms the outputs of the expert and strategic workshops. The UK has research strength in basic bioscience and in engineering, but these skills have not yet to be fully applied in the bioenergy sector (Table 4). Capabilities are seen to be **high** in relation to: basic bioscience; research in plant genomics, breeding and agronomy; engineering solutions for future technologies; and environmental impact and life cycle assessment (LCA) of new energy systems. Capabilities are **medium** in relation to: demonstration and deployment of existing technologies; and the development of co-firing technologies and clean coal solutions. Capabilities are **low** in relation to: developing the 'whole-chain' for utilisation of biomass from diverse sources; improved technologies for utilisation of energy from waste; and the development of the bio-refinery concept for R&D and second generation biofuels. The UK is also perceived to have **high** capability levels in relation to phenomics and environmental impact assessment.

Table 4: UK's perceived capability levels to address future bioenergy research challenges

<table>
<tr><th colspan="4">High capability levels</th></tr>
<tr><th>7</th><th>8</th><th>9</th><th>10</th></tr>
<tr><td>Good on biomass, OK on bioconversion. Average on pull-through.</td><td rowspan="2">Good capabilities and resources compared to outside UK, but not compared to other research communities.</td><td rowspan="5"></td><td rowspan="5">But we won't achieve it without integration of activity.</td></tr>
<tr><td>Good pockets of excellence. Reasonable coordination. Ability to bring in expertise.</td></tr>
<tr><td>World leading bioscience, some problems around cross-discipline funding and policy/industry pull.</td><td rowspan="2">Have the fundamental skills but further effort needed to apply them to real world challenges, i.e. take all the way through to commercialisation.</td></tr>
<tr><td>Generally a good base to start from but will need a lot of effort to see it through.</td></tr>
<tr><td>Good at TRL 1-4; erratic at TRL 5-9.</td><td>Wide diversity, possibly lacking in commercialisation and detail in specific sectors.</td></tr>
</table>

<table>
<tr><th colspan="4">Medium capability levels</th></tr>
<tr><th>4</th><th>5</th><th>6</th><th>6.5</th></tr>
<tr><td rowspan="6">Breadth of research is good but patchy and not integrated in all aspects</td><td>Poor integration of science, technology, funding, and with industry.</td><td>Great science, poor integrated translation.</td><td rowspan="6">Increasing capacity and coordination, but much more to do.</td></tr>
<tr><td>UK has come late to analysing the challenge and applying itself to the solution.</td><td>Some good fundamentals but need a systems approach, policy certainty and socio-economic overview.</td></tr>
<tr><td>Science, engineering, biology and agronomics are good. Social and economic, public awareness is low.</td><td>Good research across different disciplines, increasingly integrated, but lacking depth of application in bioenergy overall.</td></tr>
<tr><td>Good basic – not sure if we can translate to action.</td><td>Good groups collaborating well with sister groups but needs more good people working in a more integrated manner across the bioenergy sector.</td></tr>
<tr><td>We have high capability but it could all be easily lost.</td><td>Strong research base but disconnect with political drivers and practical deliverability.</td></tr>
<tr><td>Excellent science base but: not integrated enough; not supported at scale needed.</td><td>Breadth of research is good but patchy and not integrated in all aspects.</td></tr>
</table>

<table>
<tr><th colspan="4">Low capability levels</th></tr>
<tr><th>0</th><th>1</th><th>2</th><th>3</th></tr>
<tr><td colspan="4">No scores assigned</td></tr>
</table>

The SUPERGEN Biomass consortium supported by EPSRC (now the SUPERGEN Bioenergy Hub[27]) is identified by the UKERC Landscape document as one of the key elements of the UK effort and is part of the RCUK Energy Programme (RCEP). The Hub, funded through to 2017, acts as a focal point for sharing and dissemination of scientific knowledge and engineering understanding to facilitate near-term deployment of technologies; investigates and develops new approaches for dealing with the very significant engineering challenges associated with deployment of more novel technologies; improves scientific understanding of the fundamental aspects of different forms of biomass and its conversion; takes a whole-systems perspective to comprehensively evaluate the potential of future technology options; and adopts an interdisciplinary approach to look beyond the engineering and technical aspects of bioenergy and ensure adequate consideration of the impacts on ecosystems, social responses to technology deployment and the economic context of policy development.

The other key element of the early stage R&D landscape is the BBSRC Sustainable Bioenergy Centre (BSBEC).[28] This brings together 12 universities and institutes and also forms part of RCEP. The Centre tends more towards basic science than the SUPERGEN Bioenergy Hub and conducts its work around six programmes: perennial bioenergy crops; cell wall sugars; cell wall lignin; lignocellulosic conversion to bioethanol; second generation bacterial biofuels; and marine wood borer enzyme discovery. In spite of its more scientific orientation, the Centre has 14 industrial associates. BBSRC also funds an Energy Champion to develop and coordinate the work of BSBEC and forge links with national and international policymakers and other funders of sustainable bioenergy research. The role of Energy Champion is perceived to have had a positive impact, notably in bringing industrial perspectives into the academic domain. BSBEC's current phase of funding is from 2009-14.

The potential value of more connection between BSBEC and the SUPERGEN Bioenergy Hub was noted at the expert workshop which engaged both communities. EPSRC and BBSRC also support bioenergy research through their responsive modes. The BBSRC Rothamsted Research Centre is an important locus of bioenergy-related research as is the independent John Innes Centre which receives strategic support from BBSRC. The Natural Environmental Research Council's (NERC's) Centre for Ecology and Hydrology (CEH) has a significant interest in the ecological implications of bioenergy deployment. UKERC has also conducted system-level research on bioenergy and ecosystem impacts under its Phase II Energy and Environment theme.[29]

Moving into the more applied R&D sphere, the Technology Strategy Board (TSB) supports bioenergy through its energy priority area. TSB's primary aim is to accelerate economic growth by stimulating and supporting business-led innovation. Energy is included within its portfolio because of its economic importance to the UK. Along with the research councils, TSB supports **catalyst centres** which support projects in priority areas where the UK research base has a leading position and where there is clear commercial potential. Catalyst centres take projects from research to as close to commercial viability as possible. TSB operates an **Agri-tech catalyst** with BBSRC which includes bioenergy within its remit. An energy catalyst centre jointly funded by EPSRC is in preparation. Energy accounted for 12% of TSB's £147m spend on thematic interventions in 2012/13.[30]

The Energy Technologies Institute (ETI) is a public-private partnership with three public sector members – DECC, the Department of Business (BIS) and EPSRC - and six private sector members (BP, Caterpillar, EDF, E.ON, Rolls Royce and Shell). Bioenergy[31] is one of ten programme areas. The overall aims are:

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27 http://www.supergen-bioenergy.net/

28 http://www.ukerc.ac.uk/support/BSBEC_homepage

29 http://www.ukerc.ac.uk/support/Energy+and+Environment

30 Technology Strategy Bard, **Annual Report and Accounts 2012-13**, HC 567, London: The Stationery Office. http://www.official-documents.gov.uk/document/hc1314/hc05/0567/0567.pdf

31 http://eti.co.uk/downloads/related_documents/7656_ETI_Bio_WEB.pdf

to develop an understanding and assessment of the economic value chains and carbon impact of sustainably developing UK biomass resources and to assess the landscape and opportunity for meaningful technology acceleration and demonstration. Five bioenergy projects have been supported: gasification plant design competition; ecosystem land-use modelling (ELUM); biomass to power with CCS; flexible research biomass systems value chain modelling; and energy from waste. ELUM involved quite basic research assessing the impact of bioenergy crop land-use changes on soil carbon stocks and greenhouse gas emissions. It filled a perceived gap that had not been covered by previous research council–supported work. ETI is also evaluating bioenergy linked to CCS.

The UK lacks pilot scale development facilities such as those that have been developed in the US and Brazil. The activities of all of the UK energy research and energy innovation bodies are linked through the LCICG.[32]

3.5 UK participation in EU and international activities

UK organisations have been active in the EU Framework RTD (research and technology development) Programmes. FP7 supported 16 bioenergy projects, of which the UK participated in ten and co-ordinated three.[33] These included two ERA-NET plus projects, **BESTF** and **BESTF2**, which aimed to bring together national and transnational initiatives in the field of bioenergy, and were led by TSB. The UK (University of York) also led the **SUNLIBB** project on sustainable liquid biofuels from biomass bio-refining. The Climate Knowledge and Innovation Community (**Climate-KIC**) led by Imperial College London, funded through the European Institute of Innovation and Technology (EIT), also has a pipeline of projects relevant to bioenergy and the broader bio-economy.

UKERC participates, on behalf of the UK, in the Joint Programme on Bioenergy[34] established through the European Energy Research Alliance (EERA) under the EU Strategic Energy Technology Plan (SET-Plan). Under the SET Plan, a European Biofuels Technology Platform (EBTP)[35] (also referred to as a European Industrial Initiative (EII)) represents industry interests. BP is a member of the Steering Committee.

The UK is a signatory to the IEA Implementing Agreement (IA) on Bioenergy[36] whose vision is to achieve a substantial bioenergy contribution to future global energy demands by accelerating the production and use of environmentally sound, socially accepted and cost-competitive bioenergy on a sustainable basis. The IA operates ten tasks of which the UK participates in six: biomass combustion and co-firing; pyrolysis of biomass; integrating energy recovery into solid waste management (UK lead); energy from biogas; sustainable international bioenergy trade: securing supply and demand; and biomass feedstocks for energy markets.

4. Existing roadmaps and innovation needs assessments

4.1 Introduction

Reflecting the scope and diversity of bioenergy chains and applications a number of roadmaps and other assessments relevant to bioenergy have been established in the UK, the EU and elsewhere. Some address bioenergy in general while others are focused on specific applications such as aviation, transport biofuels or biomass for heat and power. This section summarises the scope of various exercises in the UK, the EU, the IEA, the US and Brazil.

32 http://www.lowcarboninnovation.co.uk/
33 http://cordis.europa.eu/projects/home_en.html
34 http://www.eera-set.eu/index.php?index=26
35 http://www.biofuelstp.eu/
36 http://www.ieabioenergy.com/

4.2 UK

The UK's policy on bioenergy is framed by the **UK Bioenergy Strategy** published in 2012.[37] This is a policy document rather than an R&D roadmap but it does address issues relating to the long-term development of bioenergy. The preceding Committee on Climate Change (CCC) **Bioenergy Review**[38] had cautioned against the setting of long-term bioenergy targets pending the establishment of regulatory arrangements to ensure achievement of sustainability objectives. While the Government's response was cautious in this respect, it acknowledged the need for further analysis, pointing towards an element of any forward research agenda. The Strategy also signalled that the availability of BECCS would be a key factor determining the most appropriate use of biomass. Again, this signals an important element of the bioenergy research agenda. Finally, the Strategy described biosynthetic gas, hydrogen and advanced biofuels as providing key hedging options against inherent long term uncertainties in the bioenergy arena. This points clearly to the need for R&D in these areas.

The LCICG published the Summary Report of its **Technology Innovation Needs Assessment** (TINA) for bioenergy in 2012.[39] The report identified bioenergy as a low carbon provider of each of its potential end products, renewable gas, heat, electricity and transport fuel potentially meeting upwards of 10% of UK energy demand by 2050. The bioenergy pathways most robust to uncertainty were: biomethane from anaerobic digestion (AD); and biopower in combination with CCS if CCS is available. The report found that most conversion technologies are unproven at scale and are not yet cost-competitive. Innovation in bioenergy could reduce UK energy costs by between £6bn and £101bn between now and 2050, with the greatest gains coming from innovations to maximise the yields of dedicated energy crops and enable reliable operation of early stage conversion technologies. Specifically, the report identified the areas with the biggest benefit being:

- woody/grassy crops with greater yields, which can be grown on marginal land in a way that does not compromise the delivery of important ecosystem services;
- affordable and reliable advanced biofuels from sustainable crops (e.g. gasification systems, liquid pyrolysis fuels and lignocellulosic fermentation); and
- high efficiency biopower systems which are robust to a range of feedstocks and CCS requirements.

Sustainable feedstock production should be addressed alongside advanced conversion technologies. Work is also needed on sustainability impacts, notably the LCA of emissions.

There is no UKERC roadmap covering bioenergy. However, a **Bioenergy research roadmap workshop** brought together stakeholders and the research community in 2007.[40] This considered the appropriate scope of any full roadmap and identified the following areas as R&D priorities:

- plant improvement;
- membranes;
- cell walls;
- enzymes;
- waste biomass resource;
- microbial conversion processes;
- conversion technologies;
- scaling of biogeneration;

37 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48337/5142-bioenergy-strategy-.pdf
38 http://archive.theccc.org.uk/aws2/Bioenergy/1463%20CCC_Bioenergy%20review_bookmarked_1.pdf
39 http://www.lowcarboninnovation.co.uk/document.php?o=9
40 www.ukerc.ac.uk/support/tiki-download_file.php?fileId=171

- automotive application of biofuels;
- carbon/energy balances;
- environmental sustainability;
- economic and socio-economics;
- public perception; and
- pre-processing, e.g. pyrolysis.

In May 2013, a UK **Roadmap for Algal Technologies**[41] commissioned by the NERC-TSB Algal Bioenergy Special Interest Group was published. This covered bioenergy and biofuels alongside other applications such as bio-refining, waste water remediation and chemicals. Using algae as opposed to other forms of biomass could reduce conflicts between the use of land for food crops and energy crops However, the report notes that substantial challenges remain to be solved before the large-scale production of biofuels from algae can become a reality. The report identifies a range of pathways through which algal biomass could be converted into energy products. It found the two most promising routes to be: macroalgae for AD and microalgae for synthetic biofuels via thermochemical conversion. The former would result in the production of methane. The R&D challenges include: overcoming seasonal supply/availability of feedstock; the development of lower cost methods of macroalgae farming; biogas upgrading and clean up; and developing infrastructure to export products to point of use. Microalgae for liquid biofuels will require innovation in algal cultivation at scale to improve production efficiency, especially on harvesting and processing. Energy products could also be produced as co-products through integrated biorefining.

4.3 EU

The EII on bioenergy set up under the SET Plan has produced an indicative roadmap for bioenergy out to 2025.[42] This contains little detail other than calling for 'pilot and demonstration activities on new value chains'. The European Commission also produced a high-level bio-economy strategy in 2012.[43]

4.4 IEA

The IEA has produced two bioenergy roadmaps supporting its Energy Technology Perspectives activities, one on **Bioenergy for heat and power**[44] and the other on **Biofuels for transport**.[45] These are effectively technology deployment roadmaps but each identifies research, development and demonstration (RD&D) needs.

The Bioenergy for heat and power roadmap notes that RD&D efforts need to focus on all parts of the supply chain, including crop breeding, cultivation techniques, harvesting, pre-treatment, transport and conversion. Upstream R&D (crop breeding, cultivation and feedstock storage) may be relevant to agriculture and forestry in general and public funds might come from non-energy funding bodies. Downstream R&D needs (conversion and end-use applications) are more likely to be supported through specific energy bodies and initiatives. The IEA also notes the need: a) to develop and implement internationally agreed sustainability criteria, indicators and assessment methods for bioenergy; and b) to introduce internationally aligned technical standards for biomass and biomass intermediates, in order to tap new feedstock sources.

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41 https://connect.innovateuk.org/documents/3312976/3726818/AB_SIG+Roadmap.pdf

42 http://setis.ec.europa.eu/implementation/technology-roadmap/european-industrial-initiative-on-bioenergy

43 European Commission, 2012. **Innovating for Sustainable Growth: A Bioeconomy for Europe**, COM(2012) 60 final

44 http://www.iea.org/publications/freepublications/publication/name,27281,en.html

45 http://www.iea.org/publications/freepublications/publication/name,3976,en.html

The **Biofuels for transport** roadmap notes that a substantial amount of RD&D for biofuels has already been conducted and that a number of biofuels are already commercially deployed. The roadmap recommends that RD&D should support the whole biofuel production chain including new crop varieties, the improvement of existing crops, biomass handling and transport, and biofuel conversion. Large field trials are needed in order to develop high-yielding feedstocks that are ready for market deployment once advanced biofuels have been commercialised. Synergies between RD&D investments in biofuels and those in other sectors, such as agriculture, forestry and the chemical industry, need to be exploited.

The IEA argues in both roadmaps that international collaboration would help to reduce total RD&D expenditure and that the results from publicly funded RD&D projects should be widely accessible.

4.5 Other international activities

The US Department of Energy's (DoE's) document **Breaking the Biological Barriers to Cellulosic Ethanol: A Joint Research Agenda**[46] was published in 2006. This was produced jointly by the Office of Energy Efficiency and Renewable Energy and the Office of Science. The document focuses on second generation biomass – cellulosic biofuels - and argues that agriculture, industrial biotechnology and the energy sector can be linked to promote climate protection and energy independence. The report is comprehensive in its scope, breaking the research agenda into the areas set out in Table 5 under the banner 'Systems Biology to Overcome Barriers to Cellulosic Ethanol'.

The DoE Office of Energy Efficiency and Renewable Energy also sponsored a **National Algal Biofuels Technology Roadmap** which was published in 2010.[47] The high-level conclusion was that many years of both basic and applied science and engineering would be needed to achieve affordable, scalable, and sustainable algal-based fuels. Like the **Biological Barriers to Cellulosic Ethanol Roadmap**, this is a comprehensive assessment that structures its recommendations round four broad areas: feedstocks; cultivation; harvesting/de-watering; and conversion. Table 6 summarises the R&D challenges identified.

IN 2011, the US DoE updated a previous strategic analysis, **US Billion-Ton Update: Biomass Supply for Bioenergy and Bioproducts Industry**,[48] assessing whether US agriculture and forest resources have the capability to produce one billion dry tons of biomass annually, in a sustainable manner. The report focused on biomass that was potentially available, even though some potential feedstock would more than likely be too expensive to actually be economically available. The report also included: a spatial, county-by-county inventory of primary feedstocks; supply curves for the individual feedstocks; and rigorous treatment and modelling of resource sustainability.

A number of other countries have produced roadmaps related to bioenergy. One notable example is the 2013 **Flightpath to Aviation Biofuels in Brazil: Action Plan**[49] produced jointly by Boeing, Embraer, Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP) and Universidade Estadual de Campinas (UNICAMP). As the title suggests, this is a deployment roadmap, but it reaches a number of conclusions about RD&D needs. Specifically, it recommends:

- agronomic research, particularly on non-traditional feedstocks;
- evaluation of the long term impact of biomass collection on soil water and biodiversity;
- evaluation of existing available industrial waste residue feedstocks;

46 http://genomicscience.energy.gov/biofuels/2005workshop/b2blowres63006.pdf
47 http://www1.eere.energy.gov/bioenergy/pdfs/algal_biofuels_roadmap.pdf
48 US Department of Energy. 2011. **US Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry**. R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN. 227p
49 http://www.fapesp.br/publicacoes/flightpath-to-aviation-biofuels-in-brazil-action-plan.pdf

- establishing test sites that generate long-term data to support feedstock operation methodologies as a platform for soil, water and biodiversity studies;
- process research on refining technologies;
- the establishment of pilot plants for the most promising alternatives; and
- the establishment of demonstration and first-of-a-kind commercialization plants.

Table 5: Research challenges identified in the US Biological Barriers to Cellulosic Ethanol Roadmap

Lignocellulosic biomass characteristics	• Structure and assembly of cell walls • Factors in recalcitrance of lignocellulose processing to sugars • Optimization of plant cell walls
Feedstocks for biofuels	• Creation of a new generation of lignocellulosic energy crops • Ensuring sustainability and environmental quality • Model systems for energy crops • The role of GTL capabilities for systems biology • Development of high-productivity biodiesel crops
Deconstructing feedstocks to sugars	• Determining fundamental physical and chemical factors in the recalcitrance of lignocellulosic biomass to processing • Developing better enzymatic systems for biological pretreatment: ligninases and hemicellulases • Understanding the molecular machinery underpinning cellulose saccharification: cellulases and cellulosomes • Harvesting the biochemical potential of microorganisms through metagenomics • Characterizing cell walls using high-throughput methods • Simplifying the bioconversion process by understanding cell-wall deconstruction enzymes expressed in plants
Sugar fermentation to ethanol	• Optimizing microbial strains for ethanol production: pushing the limits of biology • Advanced microorganisms for process simplification
Crosscutting science, technology, and infrastructure	• Analytical tools to meet the challenges of biofuel research • Imaging technologies • Microbial cultivation • Data infrastructure • Computational modelling

Source: US DoE

Table 6: Research challenges identified in the US National Algal Biofuels Technology Roadmap

Algal biology	• Strain isolation, screening and selection • Algal physiology and biochemistry • Algal biotechnology
Algal cultivation	• Cultivation pathways • Scale-up challenges
Downstream processing: harvesting and dewatering	• Approaches for microalgae • Approaches for macroalgae • Systems engineering
Extraction of products from algae	
Algal biofuel conversion technologies	• Direct production of biofuels from algae • Processing of whole algae • Conversion of algal extracts • Processing of algal remnants after extraction
Co-products	• Commercial products from microalgae and cyanobacteria • Commercial products from macroalgae • Potential options for the recovery of co-products
Distribution and utilization	• Distribution • Utilization
Resources and siting	• Resource requirements for different cultivation approaches • Integration with water treatment facilities • Co-location of algal cultivation facilities with co2-emitting industries
Systems and techno-economic analysis	

Source: US DoE

5. High-level research challenges

The challenges identified in this section derive primarily from the shared insights of representatives of each of these communities who attended the Rothamsted expert workshop. Research challenges in the bioenergy field need to draw on many scientific disciplines including: the biological sciences in relation to crop production and biological conversion; engineering in relation to harvesting, transport and logistics; the environmental sciences in relation to biodiversity and impacts on ecosystems services; economics in relation to supply chain issues; and social sciences in relation to public perceptions and acceptability.

The wide ranging challenges fall into six broad topic areas as shown in Table 7 which also identifies the area of science within which (and implicitly, the research councils within whose areas of interest) the challenges lie. Three important themes ran through discussions at the workshop reflecting the systemic nature of the bioenergy challenge.

The first is the need to look at bioenergy chains holistically. Crop properties and the methods for converting those corps into commercial products are closely related. Crops can be 'designed', through selective breeding or genomics, to be more easily converted and put into use. If conversion processes are thermo-chemical in nature, this suggests the need for interaction between those working in the biological sciences and those working in engineering and the physical sciences. Second, some bioenergy conversion processes may be hybrid in nature, combing biological and thermochemical techniques. Again, this requires interaction between biology and engineering. Third, sustainability poses major challenges for bioenergy development in terms of lifecycle GHG emissions, land use, water availability and biodiversity. This implies the need for strong links between environmental scientists and biologists. These scientific interactions have implications for research support which are drawn out in Section 6.

Tables 8-13 draw out the more specific research challenges associated with each of the topic areas identified in Table 7.

Table 7: Research challenges by broad topic area

Topic areas	Challenge areas	Science area
Novel solutions and fundamental research	• Novel solutions • Novel production organisms • Novel technologies	Biological sciences Engineering
Bioenergy applications and product improvement	• Improving product quality • Improving conversion yields • Transport fuels	Biological sciences Engineering
Risk, resilience and climate change	• Resilient crop productivity improvement Energy crops on marginal land • Perennial bioenergy crops to ameliorate the impacts of intensified arable crops • Residue utilisation • Risks of investing in biomass crops	Biological sciences Environmental sciences Engineering Economics
Bioenergy systems and supply chains	• Best use of biomass • Decision support tools • Optimisation and integration • Transport and remote locations • Commercialisation	Engineering Economics Social sciences
Sustainability	• Delivering carbon benefit • Land use • Other sustainability issues	Biological sciences Environmental sciences Economics Engineering
Social acceptability	• Social acceptability	Social sciences

Table 8: Research challenges - novel solutions and fundamental research

Challenge area	Challenges
Novel solutions	• Capturing energy from the sun • Synergies with geo-engineering (e.g. change in albedo) • Bioluminescent lighting • Speeding up multiplication and establishment of elite lines – yield, carbon, photosynthetic rates • Fundamental research into lignocelluose breakdown and sugar and lignin processing
Novel technologies	• Conversion of CO_2 into chemicals • Synthetic biology to generate new 'classes' for bioconversion • Artificial photosynthesis • Hybrid biological and thermo-chemical processing. • Cost-effective ways of utilising lignin
Novel production organisms	• Algae (micro and macro) • Fungi that produce biodiesel

Table 9: Research challenges - bioenergy applications and product improvement

Challenge area	Challenges
Improving product quality and yield during conversion	• Catalysts for improving yield performance and selectivity of conversion and upgrading processes • Conversion and processing technologies to extract full product yield • Liquid separation • Conversion systems utilising a variable feedstock mix • Comprehensive evaluation of bioenergy/biofuel system performance, yield, cost, environment, socio-economics and bio-products
Transport fuels	• Applying liquid fuels technology to aviation and shipping • Production of high-performance liquid biofuels for aviation • Fuel-flexible transport systems • Incorporating bioenergy into public transport • Policy/regulatory mechanisms for decarbonisation of aviation and shipping

Table 10: Research challenges associated with risk, resilience and climate change

Challenge area	Challenges
Resilient crop productivity improvement	• Maintaining high feedstock yields while adapting to market demand • Improving crops and perennials: higher yields, lower water use, better fuel quality, using greater quantities of CO_2, better usages of N/P/K and more resilient to climate change • Speeding up multiplication and establishment of elite lines – yield, carbon, photosynthetic rates etc. • Development of energy crops adapted to future climates • Resilience to climate change and extreme weather events • Crop productivity and water demand
Energy crops on marginal land	• Supportive practical, specific agronomy for energy crops • Joint use of land for bioenergy and other purposes (e.g. wind turbines) • Increasing biomass yields on lower grade land without substantially increased inputs (nutrients, water) • Identifying high-yielding crops to be grown on low-grade land, including innovative, flexible production systems. • Creation of energy crops that produce high yields on marginal land and are resilient to climate change
Residue utilisation	• Flexibility, continuity and security of supply • Impact of extreme weather events and disruptive climate change on crop residues
Understanding the risks of investing/switching to bioenergy crops	• Security and seasonality of supply • Flexibility and adaptability to environmental change and other circumstances • Risk mitigation

Table 11: Research challenges - bioenergy systems and supply chains

Challenge area	Challenges
Best use of biomass	• Optimising bioenergy use • Best use of biomass in transport, heat, electricity and co-gen: value and flexibility • Feasibility studies of different technologies • Increasing the value of biomass by diversifying the range of production • Multiple use feedstocks for bioenergy in relation to economic and environmental sustainability
Decision support tools	• Techno-economic modelling for whole-system optimisation • Finding the optimal solution in whole system analysis
Optimisation and integration	• Utilisation of biomass • Integration of bioenergy technologies to improve overall energy ratio/gain. • Integration with conventional cropping systems • Co-products from a single feedstock • Multiple/ higher-value added products, e.g. fuels, materials, from bio-refineries • Use of conventional crops in bio-refineries • Ash utilisation and configuration/operation of energy conversion technologies so that ash is a product not waste. • Landscape level research and planning • Process optimisation and integration covering algal biomass production, use of nutrients, carbon storage and capture, energy inputs.
Transport and remote locations	• Logistics for UK applications (nurseries/planting/harvesting/storage/ transport) • Storage and handling of biomass fuels • Biomass as a carbon sink by using waste for bio-products • Agricultural machinery, handling and operations at multi-scale UK applications • Efficiency of biomass haulage and handling
Commercialisation	• The role of standards to underpin commercialisation. • Safety aspects • Small-scale local production, especially in developing countries. • Adapting technology to environmental/local constraints • Commercialisation and technology transfer

Table 12: Research challenges - sustainability

Challenge area	Challenges
Delivering carbon benefits	• High-value products that maximise efficiency • Viability of large-scale bioenergy CCS • Bio-based negative emissions technology (CCS) will be used in 2030-2050 and • Impact of BECCS on the rest of the energy system • Negative carbon chains: in terms of soil carbon, emissions to air, and biomass standing stock • Time dependency of bioenergy chains in terns of above and below ground carbon stocks
Land use	• Understanding better the environmental impact of land use change • Establish 'opportunity' maps for different land uses in the UK • Impact of changing land use on biodiversity • Landscape management • Understanding the UK natural resource base and how it can be matched to end uses • Understanding land resource, land use competition and land use change taking account of social, practical, economic and ethical issues • Comparative advantage of alternative land uses at the global level • Understanding, global land use systems from a sustainability perspective taking account of food, feed, fibre, energy, ecosystem services and biodiversity
Other sustainability issues	• Integrated approach to the sustainability challenge– air, water, soil, land use, biodiversity, social perceptions • Food/energy/land use/water nexus • Water contamination • Water availability • Soil management • Anaerobic digestion: efficiency, ammonia emissions and digestate disposal • Nutrient recycling, by-product re-use and recycling • Appropriate technology and feedstock use taking account of food/fuel/substitute materials/carbon balances • Full-system analysis in terms of ecosystem services, e.g. feed-stock production, conversion technology, transport, pre-treatment, cropping technologies • Accounting for non-energy co-products in sustainability analysis

Table 13: Research challenges – social acceptability

Challenge area	Challenges
Social acceptability	• Understanding public perceptions and acceptability of bioenergy • Promote improved public understanding of where energy/food comes from • Understanding social acceptability in terms of: aesthetics; landscape; biodiversity; stakeholder diversity; role of farmers • Links between bioenergy and welfare/quality of life • Employment impacts of bioenergy deployment

6. Research support

6.1 Ways of working

General

The strongest messages coming from the bioenergy community relate to interdisciplinarity, collaborative working between the research councils and data curation. Supporting this, there is a desire to see a reliable database of expertise, facilities and people with open access for relevant researchers and stakeholders. An academic eBay and/or social network has also been suggested. Options for hosting such a database could fall to the research councils themselves or to a research 'champion' with cross-Council responsibilities.

Cross-Council working

There is a strong desire to see the research councils working collaboratively through jointly funded programmes. Stronger links between BBSRC and EPSRC are a particular priority. The approach currently taken in industrial biotechnology could be adopted specifically in relation to bioenergy. Working separately risks topics such as combined biological/thermo-chemical conversion of biomass being neglected.

A coherent vision which cuts across the research councils would support this. The development of such as vision could involve government, landowners and industry as well as academia. The EU ERA-NET provides a good example of collaboration between different funding bodies.

Funding processes

There is a view that the research councils should develop strategic themes and goals in terms of impact while avoiding over-prescription and allowing flexible, interdisciplinary working. Specifically, opportunities should be provided to shift focus mid-project if more productive lines of enquiry emerge. Continuously open calls supported by interdisciplinary review panels would be one means of encouraging flexibility and research adventure.

Some sections of the community believe that new Principal Investigators (PIs) should be encouraged into the bioenergy field. Senior researchers from outside the field could be encouraged to 'convert' to bioenergy research. Interdisciplinarity could be the norm for a new generation of PIs.

Good links with industry at the project level would help to pull research through to commercialisation. Some feel that the research councils should support more applied R&D though other bodies, such as ETI and TSB, operate in this space.

Interdisciplinarity

Bioenergy research depends on interdisciplinary working and greater funding support for interdisciplinary projects should be made available. However, it is acknowledged that interdisciplinary research cannot be forced and links between groups should be allowed to grow organically. Collaborators need to understand the wider context. Scientists need to appreciate social and economic perspectives while social scientists and economists need to understand the limits of science.

The option of a collaborative centre for interdisciplinary bioenergy research was mooted at the expert workshop. This would help to encourage shared skills and learning.

6.2 Long-term perspectives, infrastructure and facilities

In the BBSRC world, there is no equivalent to the support for ships/satellites from NERC. The main 'infrastructure' need in order to progress bioenergy research is support for extensive field trials. Plants need to be tested in different environments and results compared. Full monitoring of trials is essential. There is a belief that longer term trials of ten years or more would deliver better scientific results. However, longer funding periods would need to include suitable break points in order to exit unproductive lines of research.

Funding for plant breeding is needed as are advanced computing facilities to support crop research.

Bioenergy is a relatively new field and, if it is to become established, will need long-term support. Longer term continuity in funding, analogous to UKERC with Phase III renewal, would be useful. It is acknowledged that BBSRC is attempting to address issues such as the length of funding cycles, the balance of blue skies/applied research, and industrial engagement/knowledge exchange in the Networks in Industrial Biotechnology and Bioenergy (NIBB) call.

6.3 Data

There is widespread support for the general principle that data and reports generated through research supported by the research councils should be available to all researchers and the wider public. This avoids re-inventing the wheel and can speed the road to commercialisation. While it is acknowledged that BBSRC (and EPSRC) have a formal data policy and require data to be retained and shared, there is a widespread belief that the mechanisms need improvement. Central data platforms and mechanisms for sharing data and information between research groups and between academia and industry are essential. The relevant data would cover: genomics, crop traits and physiology and crop improvement.

In partnerships with industry, arrangements for data sharing tend to be better worked out. However, with public support, it can be hard to raise funds for data curation because, to demonstrate value, the thresholds are high. It is notable that 10% of some EU project funds go for data management and curation.

7. Training

General

Although the research councils currently support training only at the doctoral level, there was considerable interest in undergraduate and Masters-level training at the expert workshop. The relative lack of courses at these levels was noted, notwithstanding Masters courses at the Institute of Biological, Environmental and Rural Sciences (IBERS) and Nottingham. There was some interest in the research councils supporting masters-level training if capability or requirement could be demonstrated.

Beyond PhDs, there was a view that scholarships and fellowships in bioenergy should be earmarked.

PhD funding models

There is widespread support for embedding studentships and training programmes in large interdisciplinary projects, in a way similar to UKERC. Most Masters/PhD students go into industry or policy rather than academia and the skills acquired in the course of collaborative work would be valued. Seconding PhDs into industry, as with Collaborative Awards in Science and Engineering (CASE) studentships, would be a useful way forward. It was noted at the expert workshop that industry wants conventional degrees, rather than specialist degrees, and team-workers, rather than individualists.

Understanding of policy/markets

There is a need for research scientists and engineers to be educated in the role of economics, markets and how the business world works. This would help them understand the implications of their research and how to put their ideas into practice at all stages towards commercialisation.

Scientists should receive training in communication in order to be able to communicate with the wider public about research initiatives.

8. Connections

8.1 Connections across research areas

This area has connections with:

- **Transport Energy** (**Prospectus Report 4**)[50] in respect of the utilisation of transport biofuels;
- **Fossil fuels and CCS (Prospectus Report 5)**[51] in respect of combustion and conversion processes and carbon capture and storage;
- the BBSRC NIBB and the TSB-BBSRC **Agri-tech Catalyst**;[52] and
- the NERC **Valuing Nature Programme.**[53]

8.2 Linkages outside the Research Council sphere

General

Most of the discussion at the expert workshop dealt with links between the research community, industry and landowners. However, the wider point was made that the research councils, working together with other LCICG members, should develop a shared vision for bioenergy research taking the Government's bioenergy strategy[54] as a starting point. This would provide academia and industry with an overview of research topics that are translatable into practice. Good connections with the policy world are needed. There is also a strongly expressed view that better collaboration and coordination with EU programmes and wider international initiatives would be fruitful.

Links with industry and land owners

The central theme of discussion at the expert workshop was the gap between research supported by the research councils and commercial application. Independent extension services, such as those once provided by ADAS, are being missed. Good things happened under SUPERGEN Bioenergy but this was almost by accident. Collaborative efforts between academic and industry, and between the research councils and TSB, are needed to apply knowledge gained at basic research stages to more applied development, and to feed knowledge gained at later applied stages back into basic research.

Closer associations between academics and industry, as well as secondments and other forms of people movement, would smooth the path between basic research and commercialisation. Research

50 https://workspace.imperial.ac.uk/rcukenergystrategy/Public/reports/Final%20Reports/RCUK%20ESF%20Prospectus%20-%20Transport%20Energy.pdf

51 https://workspace.imperial.ac.uk/rcukenergystrategy/Public/reports/Final%20Reports/RCUK%20ESF%20prospectus%20-%20Fossil%20fuels%20and%20CCS.pdf

52 https://www.innovateuk.org/agri-tech-catalyst

53 http://www.nerc.ac.uk/research/programmes/valuingnature/

54 Department of Energy and Climate Change, **Bioenergy Strategy**, April 2012. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/48337/5142-bioenergy-strategy-.pdf

council-sponsored industry clubs might be a way forward. Some researchers have argued that industry needs to better understand and support the research base with a view to protecting their own long-term profitability and resilience.

There is a wider issue that is beyond the remit of the research councils with regard to the funding of demonstration plants and the subsequent disconnect between demonstration plant and fully commercial activity. If academics had access to funds for larger scale pilots this would enable them to scale up their operations. The research councils can support 'pilot scale' projects, but this depends on the definition of 'pilot scale' and the level of funding required.

Access to land is important for conducting crop research and better relationships need to be built with landowners.

It has been noted that links between the research communities and small-to-medium sized enterprise (SMEs) is a particularly difficult as small companies cannot afford to attend, for example, SUPERGEN meetings.

8.3 Other issues

The importance of having a vision for bioenergy research covering outcomes, challenges and objectives has been noted. Some at the expert workshop argued that a carbon vision rather than an energy vision was needed.

A horizon-scanning capability would ensure that opportunities for novel research are not lost. The research councils should ensure that they are open to proposals relating to more novel technologies and solutions.

9. Conclusions and recommendations

Bioenergy meets about 10% of world energy demand, most of it in the form of solid biomass. The role of bioenergy in future energy systems various widely across different energy outlooks and scenarios, both globally and at the UK level. One of the reasons is increasing concern about the life cycle GHG emissions associated with certain bioenergy chains and wider sustainability impacts. At the same time, there is a growing perception of an abundance of fossil fuel resources. It has been estimated that one fifth of global energy could be provided by biomass without damaging food production, though fossil fuel producers' estimates of the bioenergy contribution to global energy by 2040 are in the range 7-10%. In the UK, different scenarios envisage bioenergy meeting 5-25% of energy demand by 2040. Much of that wide variation is accounted for by differences in assumptions about the availability of imported biomass. Bioenergy could be deployed in markets for power, heat and transport fuels. The availability or otherwise of CCS is a key differentiator in terms of future markets for bioenergy. Without CCS, the most appropriate use of biomass would probably lie in transport fuels. With CCS, removing CO_2 from the atmosphere through BECCS technology becomes an option. Given uncertainties, RD&D strategies should be designed to prepare for a wide range of futures for bioenergy.

There is wide agreement that the UK has considerable scientific strengths relevant to bioenergy, especially in relation to crop breeding, genomics and growing biomass. There are also strengths in relation to biomass conversion. The bioenergy research community displays greater self-confidence about its capabilities than do most other UK energy research communities. BBSRC and EPSRC have made important investments supporting their respective communities. However, industrial capabilities are perceived to be weaker and improved collaboration along the innovation chain is deemed desirable.

‘Bioenergy’ is a system comprising many diverse supply chains and hence research needs are varied and complex. Research needs identified in this report range from fundamental to applied and fall into six main areas: fundamental research and novel solutions; applications and product improvement; risk, resilience and climate change; bioenergy systems and supply chains; sustainability; and social acceptability. These reflect research needs identified in a range of roadmapping exercises conducted in the UK and internationally.

Fundamental research is needed to address the breakdown of lignocellulosic material in cells to underpin next generation biofuels with lower life cycle GHG emissions. Other lines of enquiry concern genetic manipulation to alter biomass composition, prospecting genetic diversity, novel chemistry for fuels and materials, synthetic biology, artificial photosynthesis and, more speculatively, bioluminescent lighting. The investigation of algal biomass, including cultivation and downstream processing, is another fundamental research opportunity.

In terms of application and product improvement, the focus needs to be on improving product quality and yields during conversion. A supply chain view is needed to ensure that feedstocks and conversion processes are well-matched. Selection of catalysts is a critical factor. Designing processes that can tolerate a range of feedstocks will encourage commercial application. Systems research, and research at the agronomic level, is also needed to understand how bioenergy cropping can best be integrated into existing landscapes and systems.

The need to build-in resilience to climate change and other factors helps to define a number of research challenges. These include higher yields, lower water use, lower life cycle GHG emissions and better use of nitrogen, potassium and phosphates. Resilience to extreme weather and future climate change is also important. Designing crops suitable for cultivation on marginal land will help to minimise food versus fuel conflicts. Integrating of perennial cropping systems with annual cropping could ameliorate the impacts of climate-related flooding and drought.

A system-level view of bioenergy and bioenergy supply chains is needed. This includes whole system analysis, landscape perspectives, consideration of the most appropriate use of biomass for energy, integration of cultivated crops and processing techniques, the development of bio-refinery concepts and the utilisation of co-products. There is also a need to explore logistics along the supply chain. There needs to be research support for the development of standards to underpin commercialisation.

Sustainability throws up a wide range of research challenges but the emergence of new markets for biomass suppliers can also provide new market opportunities. A better understanding of life cycle GHG emissions and the environmental impact of land use change is critical. Exploring the viability of large-scale BECCS is part of the former challenge. ILUC must be addressed. More specific topics include a better understanding of the UK natural resource base, competition for land use and impacts on biodiversity, water use, nutrient recycling and wider ecosystems services. Finally, a better understanding of public perception and the social acceptability of bioenergy cultivation and use is needed. This needs to be framed in terms of air quality, water quality, soil, aesthetics, landscape and biodiversity as well as local environmental impacts, e.g. lorry movements associated with biomass heat and power plants.

A number of steps could be taken to enhance research outcomes in the UK. Better linkages between funding agencies are a priority. The research communities supported by BBSRC and EPSRC operate rather separately and more coordination is needed to avoid gaps in the research agenda and link activities focused at different points in the supply chain. There is also a need for better coordination between the research councils and later stage energy innovation funding bodies. The establishment of the TSB-BBSRC **Agri-tech** catalyst suggests a possible model.

There is a need to support more extensive, fully monitored field trials. Longer funding cycles may be needed, though these should be stage-gated to ensure that unproductive lines of research are discontinued. Mechanisms for curating data arising from field trials and other experiments could be improved so as to avoid re-inventing the wheel and to speed up commercialisation. Relevant data would cover: genomics; crop traits and physiology and crop improvement.

There is a perceived need to improve links between the research community on the one hand and industry and landowners on the other. Closer links would allow better access to land and would allow knowledge acquired from demonstration and applied research back to the research community.

As in other areas of energy research, there is a desire to see PhD studentships supported through large interdisciplinary programmes and projects as well as through CDTs.

Annex A: Research needs

At the expert workshop, participants broke into four main groups to assess research challenges. These covered: resilient crops; commercialisation; carbon and economic optimisation; and land use and sustainability. The main findings have been reporeds in Section 5, **High-level research challenges**. This Annex reports the more detailed research needs that were identified. A final section reports cross-cutting research needs identified during a second sweep of research challenges and opportunities.

A.1 Resilient crops

Understanding carbon partitioning in plants: lignin growth; cell walls; primary metabolites v. stress response; secondary metabolites v. reserves.

Soil/plant interactions. Plant/microbe interactions; optimising the microbial mix; carbon in the soil; carbon/water monitoring and understanding.

Efficient use of resources: light, water, nutrients.

Understand growth with low inputs. Sustaining yields on marginal lands. Might need different varieties. In context of stress factors.

Yield plateaux. To include first generation feedstocks as we can't move to second generation instantly. Evidence needed at field/plot to farm level.

Abiotic and biotic stress. Tolerance to drought, flooding etc.

Matching crops to climate/land types. What are the target crops genotypes? Climate change may make crops developed in other countries more relevant in the UK.

Post production biology. Degradation, loss of yield during storage and transport.

Genome sequencing and assembly.

Research targets for first generation energy crops. Increased oil content, high starch, high protein and links to quality.

Life cycle of perennial crops. How long do they really last? How do they change over their life time?

Robust transformation technologies for all energy crops. E.g. GM.

Harvesting/planting marginal land: agricultural engineering; what type of machinery, e.g. for winter marshlands.

Smart, rapid ways of sensing: remote sensing/surveying of field properties; on-site prediction of yield; how much biomass can be delivered annually?

Crop quality and checking. E.g. dipstick tests.

A.2: Commercialisation

Better and cheaper enzymes that could improve the rate and selectivity of processes.

Lignin degradation by biological pathways.

Proactively identifying the need for and bringing independence to standards in the bioenergy field, e.g. considering chemical components within different feedstock types.

Understanding market requirements.

A.3 Carbon and economic optimisation

Mapping carbon along supply chains. Methodologies for mapping that can be trusted. Common metrics for both current practice and forecasts.

Understanding trade-offs. Biomass for energy/carbon as compared to other uses. E.g. different energy vectors, biotechnology/chemicals (e.g. bio-refineries), biomaterials, sequestration (e.g. CCS and biochar). What economic tipping points would make energy/carbon sequestration as opposed to biomaterials the primary focus of biomass usage? Could it be seen as a 'use hierarchy'?

Lifecycle perspective. Whole lifecycle analysis needed. Not just farming, but waste products, feedstock suppliers (forestry). Map the energy/mass balance, e.g. how much carbon does it take to make the fertilizer for the crops? Map inputs and compare with forecast use.

Counterfactuals. Counterfactuals were discussed but were seen as a sensitivity within models, not the focus of a full research effort. Consider known unknowns/unknown unknowns etc. How does this apply in the real world – relevance for policymakers etc.?

Research impact. Who are we trying to influence? How are we trying to influence them and why? What language and knowledge assumptions are needed? Where do we want to be in 25 years' time?

A.4 Land use and sustainability

Policy aspects

- Focus on UK and develop framework for planning and processes for sustainable supply chains.
- Understand the system so that we understand the implications of policy change. Do we have the capacity to deal with these changes?

Systems perspectives

- Defensible whole system analysis of the global bioenergy production system taking into account spatial and temporal scales.
- Full system analysis covering the entire value chain broader impacts on supporting system, including carbon stocks, nutrient balances, water balances, etc. What are the net inputs?
- Understand system fundamentals, e.g. how much available energy in 1 kg wheat straw?
- How do we make the circular economy work properly? How do we make system sustainable in terms of resources input?
- Full system analysis of waste fuelled bioenergy systems to avoid virgin inputs into system, e.g. maize silage for AD.

Land use change

- Understand implications of UK bioenergy, both direct and indirect land use change. What are the drivers for land use change? What are the policy implications?
- Can we adopt land use change policies without impacting biodiversity, ecology, etc.? Scenarios describing how certain decisions/policies affect land use.
- Land use transition – how do ecosystems respond?

- Land management without prejudicing future operations. Consider land in terms of biggest energy potential per ha and energy balance. Gets around issue of food vs. fuel.
- Why do we need to consider land use at all? Should we instead just focus on waste biomass?
- Rather than trying to get to an optimal land use model for the UK, how do we take account of all impacts of bioenergy production?

Environment and ecosystems services

- What are the environmental implications of land use planning decisions? And how would these be measured? Ecosystem services provide a coherent framework for analysis.
- Maximising resource use, utilise wastes utilisation (most waste is of biomass origin).
- What are the transitional implications, e.g. for ecosystem services.

Biomass use

- CCC biomass potential – UK land potential versus global potential for bioenergy.
- Optimum use of biomass – conversion issue?

Measurement and tools

- Measurement and quantification (economic terms, physical terms).
- Quantification of consequences of particular intervention in terms of costs and benefits (ecosystem services etc.).
- Important to have toolkits that help decision making - how do we augment existing models and frameworks?
- Need robust, consistent, flexible tools to inform policy and the market.
- Need full system analysis, different from LCA methodology
- Multi-criteria optimisation models – final value of fuel, not just in terms of energy value. Do we need to consider biomass as future renewable carbon source of future?
- Screening tool for sensible bioenergy policies and incentives.
- Need economic models that account for resource - water, land, biodiversity - use
- Need to consider different scales – farm, catchment, economy – and different timescales
- Research question: quantification of the system (e.g., energy balance)
- What is the potential of UK biomass energy at the moment (the baseline)?

A.5 Cross-cutting points

Public perception and social acceptability. Biomass fears come from food riots, worries about food-producing land being used for energy or a lack of belief in climate change. What are the 'pinch points' at which the public get worried or involved, and what are the levers and mechanisms that can be employed to have a positive effect on public perception to influence social acceptability? We should learn from past mistakes, e.g. the original over-statement of GHG savings from bioenergy.

Incentives and trade-offs. A new type of thinking is needed on incentives. Negatives need to be communicated as trade-offs – with positive incentives, similar to the 'If you can see it, you'll benefit from it' ideas in some community wind farms. How do you balance out the different trade-offs required in a bioenergy system, how do you weight them and how do you explain that weighting to the public?

Objective policy assessment. What are the mechanisms that allow you to make 'evidence-based' trade-offs, rather than trade-offs based on personal investment or vested interests? – An objective policy assessment tool could be developed, allowing an impartial, evidence-based examination similar to the NHS's National Institute for Health and Care Excellence (NICE). Would need to be public-facing and open, and accepted by all the major public and private bodies. There would need to be an upfront acceptance that there can and will be outcomes from this tool that people will not like!

Fuels for transport. How can you transport large quantities of biofuel pellets around the UK and internationally? There needs to be an understanding of port and rail constraints – wagons designed to transport coal not pellets etc. – plus opportunities for inland water transport. Need to understand the logistics – little research on constructing and engineering ports and transport stations. Road transportation of solid fuels could be difficult, due to the volumes and designs of vehicle needed.

Spatial location and transport logistics. Most arable land and large port facilities are in the east of the UK. Spatial mapping and optimum designs for biomass infrastructure workshops are important.

Storage of biofuels. How do you control solid biomass dust? What are the key differences between it and chemical dust? We also need to understand longevity issues with regards to insects and damp. Liquid fuels such as biodiesel have a tendency to degrade – how can we prevent this? How can you handle biomass through a storage setting, and are the dust and degradation issues unique to biomass?

Transport fuels. We will need liquid fuels for some time due to the internal combustion engine. How to convert biomass, especially non-food crops, to liquids? What are the best and most efficient methods of conversion – enzyme degradation, pyrolysis, gasification?

Aviation Fuels. How do you actually prove the viability of fuels in aviation? The biofuel would need to be a 'drop-in' light fraction fuel similar to kerosene. There are fluid dynamics and combustion engineering issues, as well as questions surrounding ground handling and distribution. Research in this area would have to be closely coordinated with industry.

Rail Transport. Is electrification the most viable option for rail, or do biofuels have a role to play?

Road Transport. Fuels could be potentially ethanol/biodiesel/biobutanol/biogas. Are the barriers to uptake of biofuels in road transport policy rather than research generated? Or do the economics not work, in that oil is too cheap, limiting investment in biofuel research?

Thermal vs. biological conversion. Thermal conversion is very applied, biological conversion is currently too fundamental. There is more fundamental research required into better thermal catalysts. For biological conversion, more work is needed on engineering issues and crop modification.

Disruptive biological conversion technologies. Synthetic biology, metabolic engineering and syngas fermentation could potentially integrate the speed of a thermal process with the focus of a biological conversion process. This may require cross-Research Council collaboration to maximise benefits.

Future Biofuels. What are the desirable characteristics of future biofuels? What are the optimisation processes, both economic and technical, that need to happen to the production and conversion processes for these characteristics to be met?

Process/System modelling. We need to understand the scalability of processes rather than concentrating on scaling-up. The relationships between feedstock, technology and emissions need to be understood. Each stage of a multistage process should be examined in detail, not just the quality of the final product.

Optimisation and Integration. What are we optimising for? The bioeconomy can be considered as similar to the fossil economy – there is a supply of resource to multiple products, of which energy is only one. The system needs to be optimised from a whole-system perspective.

Biorefinery optimisation. What are the most valuable products that can be produced from biomass, both from an economic and a carbon emissions perspective? What processes do biorefineries need to implement the production of these products, and what are the most efficient refinery routes to these products?

Biorefinery research challenges. Several research challenges need to be understood with respect to biorefineries. These include cost-effectiveness, absolute versus relative greenhouse gas savings, how best to substitute for fossil fuels and the layout of modules and linkages in the refinery. Economies of scale are important – being able to scale up the processes to industrial levels is crucial.

Risks, flexibility and security. Biomass has a great deal of international supply chains – how do you make these economic and secure against disruptive events? Supply chains and operations need to be flexible and adaptable against changing circumstances. Likely variations in the composition of biofuel and the tolerance of components such as biomass boilers against changing feedstock need to be understood.

Feedstock adaptations. The geographic and climate impacts on feedstock in the UK need to be understood, as well as the potential international markets for UK feedstock.

Novel Technologies and Solutions. Research areas include synthetic biology, hybrid bio/thermal processing, CO_2 conversion to valuable chemicals, artificial photosynthesis and novel and cost-effective uses of lignin. There is a possible synergy with forestry geo-engineering – can bioenergy production be exploited here?

Novel Production Organisms. Algae, both macro and micro, could become significant players in the bioenergy sphere. Is the UK well placed to produce and utilise algae? Is algae better placed to produce high-value chemicals such as hydrogen instead of energy production? What novel conversion technologies will be needed?

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