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WORKSHOP TO DEVELOP A BIOENERGY RESEARCH ROADMAP FOR THE UK

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Executive Summary

This meeting will bring together a wide range of stakeholders – researchers, funders, policy makers and industrialists – to identify bioenergy Research Roadmap priorities for the UK, as there is no current Research Roadmap specifically tailored for the context of the UK.

Our agricultural landscape is complex but limited and the way in which UK-sourced and imported feedstock may be deployed for the competing requirements of heat, power and liquid fuel is not easily resolved. On the one hand the energy balance of heat and power may be much better than that for liquid biofuels, but on the other hand, few alternatives for liquid biofuel are available, in contrast to renewable sources of heat and power. All of this highlights the complexity of this area and suggests that such a discussion meeting is timely and will produce valuable output that captures the interdisciplinary requirements of this topic.

The scope of the meeting is to:

- Develop a clear understanding of the shared priorities for Bioenergy Research in a UK context
- Create a framework document with bullet pointed headings for further development
- Consider the nature of roadmapping and looked at other roadmaps for the USA and EU

Our conclusions will be evidence-based and our hope is that ours will be a document that helps to guide the UK Research Funding Councils and other UK agencies to 2020, ensuring bioenergy is considered in a holistic way. Our Roadmap will be published by UKERC and used as a high level document, adding to roadmaps being produced in other areas including PV and Wave and Tidal energy. This document will then be developed further following the meeting and again put out to consultation.

Preparatory documents for reading prior to the meeting

A large amount of activity has been on-going in the bioenergy area over the last few years. In the UK, several large consortia projects have kicked-off. UKERC was initiated. The Biomass Task Force reported and Government responded. BBSRC undertook a review and have a new Bioenergy initiative. BP launched a $500 M Energy Bioscience Institute. Much of this activity is summarised in the UKERC Bioenergy Road Atlas 2006.

Here, a small amount of information and some key links have been provided as background to the meeting. Please use these as to help guide your thinking before the meeting and be prepared to make contributions to developing the roadmap. Our meeting should be the beginning, and I hope that some of you at least will be there to develop the full document during the summer.

Gail Taylor April 2007

Contents

1. UKERC Research Atlas Topic: Bioenergy

Overview [http://ukerc.rl.ac.uk/ERL0304.html]

Bioenergy has an important role to play in meeting the UK aspirations in renewable energy supply for 2010 and 2020. Energy from biomass is complicated since several feedstocks (e.g. dedicated bioenergy crops such as willow, or food crops such as Oil seed rape, sugar beet and wheat) may be utilised in several conversion processes (combustion, fermentation, gasification) resulting in several energy outputs including heat, power and liquid transport fuels. It is important that this mixed portfolio of bioenergy supply is maintained at this time, ensuring the development of competitive and secure biofuels and a firm research base for future large-scale deployments. Currently, including biogas from waste, bioenergy contributes more than 80% of all UK Renewable Energy (DTI, 2004)[1] with several large-scale commercial deployments already in progress including bioethanol production and the use of biomass in co-firing and dedicated combustion. These are limited however, by low yielding feedstocks, by inefficient conversion processes and by poor environmental sustainability, enabling us to identify clear short-term research priorities for the UK. There are powerful, long-term environmental, political and economic drivers for the further development of the UK (and international) bioenergy sector. Bioenergy development in the UK has been impeded in the past largely by the persistent low cost of crude oil and associated policy and development barriers. The economic situation has undoubtedly changed and at $70 per barrel, many bioenergy operations begin to approach a commercial reality[2]. We have entered a period of sustained high fossil oil prices, with a seemingly long-term upward trend and in the future a move towards a more ‘bio-based’ economy where bio-based products (including bioenergy) are seen to have a higher value. Much advanced research will be necessary to make this move to biofuels, bio-polymers and bio-oils as well as other products, over the next two decades[3], within the appropriate framework of environmental and economic sustainability.

Despite strong multilateral interests in bioenergy R&D within the UK, split broadly between the Government departments and the Research Councils (EPSRC-led), there are international investments across the full spectrum of research, and combined UK R&D activities must be considered to be lagging behind international leaders in this field. There is clear strategic vision in Europe[4] and the United States[5], which is being matched by considerable resource investments, not least at the bioscience end of the R&D spectrum. The Biomass Task Force[11] in a recent review concluded that a reasonable assumption would be up to 1 million hectares of UK land dedicated to specialist bioenergy crops by 2020. Although it is difficult to predict the prevailing socio-economic conditions in the coming decades we would point to three clearly identifiable drivers, each of which will increase the attraction of bioenergy.

First, over the next 50 years the reserves of fossil fuels will continue to decline and those that remain will be harder to extract; high oil prices will drive R&D in renewable substitutes for petrochemicals, to ensure energy security. Secondly, land use competition will grow, making dual- or multi-use crops increasingly appealing. For example, a single crop is grown for grain, which is harvested for food and then the remaining biomass is combusted for heat or fermented to bio-ethanol. In this context the development of bio-refineries – based on the model of petrochemical refineries – where raw product (plant material) enters and more than one refined products are generated (including heat and power), is a logical ambition for biorenewable petrochemical substitution[2]. Third, atmospheric CO_2 concentrations will continue to rise well into this Century and the pressure for low-carbon energy solutions with grow alongside the increasing global impact of climate change.

A further factor that is likely to increase the economic favourability of bioenergy is the decentralisation of power generation through microgeneration (small combined heat and power units serving individual homes, businesses or communities). This will help to alleviate the need to transport biomass from point of production to large regional power stations. Microgeneration is currently a small contributor to the UK energy economy, but with careful development could become a very major one by 2030. No clear strategy currently exists in the UK to capture bioenergy from biomass 'waste' including municipal solid waste (MSW) and agricultural waste and this should be an important future priority[8].

Research Challenges

Considerable recent effort in the EU[4] and USA[5] has addressed the question of future research challenges within Bioenergy, with the publication of the Department of Energy Roadmap for biofuels[5], recent roadmap for lignocellulosic-to-bioethanol roadmap[6] and the EU Biomass Action Plan[9] and Biofuels in the European Union Vision for 2030[10]. In general, it seems likely that over a timescale of 10-20 years and beyond, there will be a move from an 'oil-based' to a 'bio-based' economy where natural resources, particularly those from green plants, can be used more effectively. This will be driven by a steady and long-term increase in the price of crude oil which currently makes bio-processing begin to look economically attractive. Many of these bio-processing routes are inefficient and still remain costly, both in necessary energy inputs and for environmental impacts, including greenhouse gas mitigation potential and other negative effects. Bioenergy from biomass can be considered a 'low quality high volume' bioresource, whilst bio-polymers, oils and other products may be considered as 'high quality low volume'. The future long-term research challenge will be to optimise the biorefinery to ensure both types of output are possible, as appropriate.

Short term Research Challenge (5 years)

- Quantify and minimize environmental impacts of bioenergy production systems using whole life cycle analysis tools ('well to wheels' type analysis)
- Identify products, co-products and routes for developing future biorefineries (bringing together biochemical and thermochemical processes)
- Improve the efficiency of bioethanol production at pre-processing, hydrolysis and fermentation steps, using biological research
- Improve deployment of CHP in the UK linked to microgeneration
- Identify optimum land-use strategies for the UK biomass resource and likely future use of arable, set-aside and marginal land in a changing climate
- Develop a UK strategy to capture energy from waste
- Improve public perception and use of GM technologies for bioenergy
- Assess the impact of bioenergy imports, including life-cycle analysis

Medium term Research Challenge (10 years)

- Improve total yield of a range of bioenergy crops, including oil seed crops, woody lignocellulose and grasses
- Improve understanding and manipulation of carbon partitioning in green plants
- Identify new and novel crops; identify new or improved products and new bacteria/yeasts from genomic research
- Develop technologies for second generation biofuels, including woody lignocellulose as feedstock and aviation fuels

Long-term Research Challenge (20 years)

- Large-scale production of second generation biofuels and deployment of biorefining complexes

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2. Bioenergy for Heat and Electricity in the UK

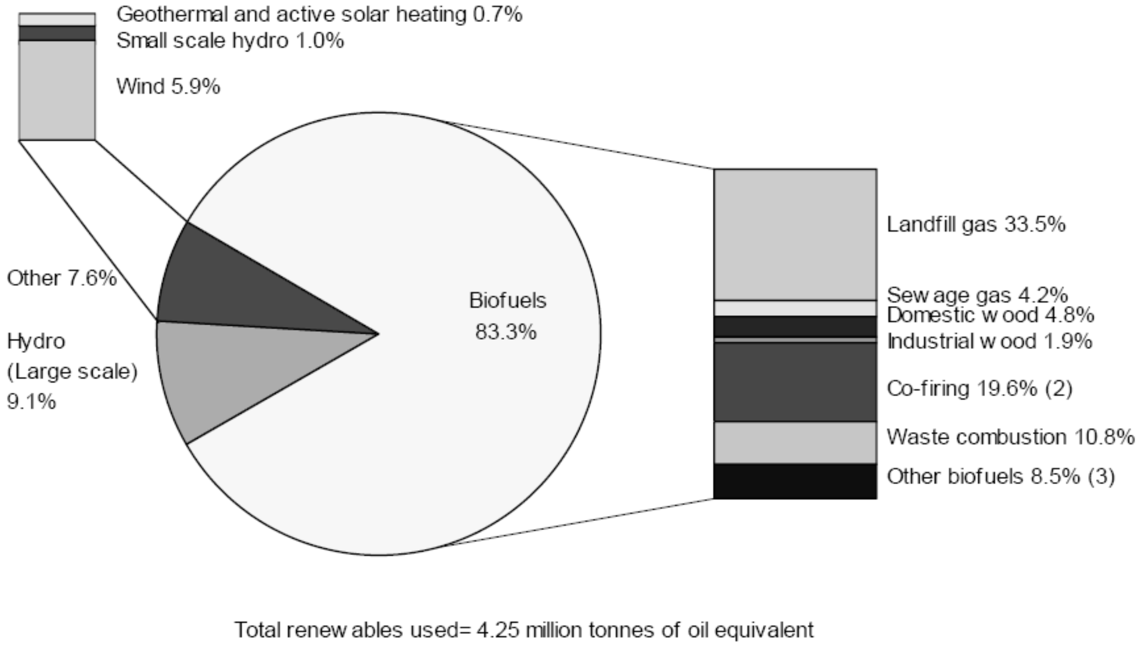
Gail Taylor, University of Southampton and UK Energy Research Centre
(A short review prepared June 2006 for the OSI Foresight scanning project in renewable energy)

Background – contribution of biomass to UK energy mix

Bioenergy from biomass is the ultimate source of renewable energy. Biomass may be defined as any biological mass recently derived from plant or animal matter including material from forests (round wood, cutting residues and other wood brashings), dedicated crop-derived biomass (woody SRC energy crops – willow and poplar, grass crops – miscanthus, timber crops), dry agricultural residues (straw, poultry litter) and wet waste (slurry, silage) food wastes, industrial and municipal waste. Bioenergy derived from these biomass streams is in general, a low carbon technology relative to the use of fossil fuels and biomass to liquid conversions.

The UK has a considerable biomass resource, estimated at an annual 20 Mt, that may be utilized as a source of renewable energy including for small-scale heat and power production using a variety of waste streams, dedicated energy crops and forest residues (Biomass Task Force, 2005)[1]. The Energy White Paper (DTI et al., 2003)[2] suggested that bioenergy could make an important contribution to the Government's energy and environment objectives, including energy security and the reduction of greenhouse gas (GHG) emissions, relative to current practices. It also highlighted the role of bioenergy in rural diversification and development. Despite this, attempts by the government to stimulate the bioenergy sector in the UK have so far had limited success, although recently this market has seen increasing activity in micro-CHP developments and the use of biomass to co-fire power stations such as DRAX[3]. The RCEP report on bioenergy (RCEP, 2004)[4] and Biomass Task Force Report[1] attribute the general lack of progress in part to a focus on promoting specific technologies without full consideration of the wider market and in part to the lack of integration of biomass supply with its utilisation and to issues of public perception and planning – a whole systems approach requiring policy incentives and investment from several Government departments.

Bioenergy for heat and electricity is complicated since several feedstocks (sources of biomass), as identified, may contribute to this output as depicted in Figure 1, for electricity generation[12]. In addition to the type of feedstock, different conversion technologies including combustion, thermal and biological routes are all possible. For electricity, bioenergy contributes over 80% of the renewable input[11], although for both heat and electricity the total contribution to the UK supply is approximately 2.5%. Specialist biomass crops include fast growing grasses such as miscanthus (commonly known as elephant grass) and coppiced trees – willow and poplar. These crops are perennial and may achieve phenomenal yields in ideal conditions producing in excess of 30 oven dried tonnes per hectare per year (ODTs) – close to the theoretical optimum[5], although these are rarely observed in commercial-scale operations. Traditional food crops such as wheat and rape may also be used for bioenergy.



(1) Excludes all passive use of solar energy and all non-biodegradable wastes.
(2) Biomass co-fired with fossil fuels in power stations.
(3) 'Other biofuels' include farm waste, poultry litter, meat and bone, and short rotation coppice.

Figure 1: The contribution of bioenergy to the generation of electricity from renewables in the UK in 2005 – data source, DTI[11]. The contribution of bioenergy to the total UK electricity supply is approximately 1.5%.

It has been estimated that of the 17 million hectares of UK agricultural land, approximately 1 million ha could be available for bioenergy crops in the future and that this could provide 8 million tonnes of energy crop[1]. Large-scale changes in the agricultural landscape in the UK may be envisaged if specialist bioenergy crops are widely planted. For dedicated bioenergy crops, all science outputs suggest that perennial crops are preferable to annual crops with a better energy ratio and more effective mitigation of greenhouse gases and yet farming practice is such that this type of agronomy may be slow to develop. Alongside agricultural feedstocks, the recovery of energy from waste streams should also be considered further since changing legislation relating to land-fill will reduce the amount of landfill gas, whilst co-firing of power stations such as Drax is a market for biomass use that has developed since 2002 and could in future utilise a large amount of dedicated biomass resource from crop supplies.

A further factor that is likely to increase the economic favourability of bioenergy is the decentralisation of power generation through microgeneration (small combined heat and power units serving individual homes, businesses or communities). This will help to alleviate the need to transport biomass from point of production to large regional power stations. Microgeneration is currently a small contributor to the UK energy economy, but with careful development could become a very major one by 2030. No clear strategy currently exists in the UK to capture bioenergy from biomass 'waste' including municipal solid waste (MSW) and agricultural waste and this should be an important future priority[8] and will now be addressed as part of the Government response to the UK Biomass Task Force report.

Current Science in the UK

Annex 1 provides an overview of current funding and scientific expertise in the use of biomass for heat and electricity. This Research atlas is being developed within the activity of the UK Energy Research Centre and will cover research, development and deployment to demonstration-scale (www.ukerc.ac.uk) and reveals a considerable increase in science activity in this area in recent years, partly because of the multiple benefits likely to arise from increased use of bioenergy, but also because of a small but strong and vocal research community. Figure 2 provides an overview of activity illustrating the fragmentation across Government Departments and limited coordination. Development of the research atlas and coordination events by UKERC should help in future to overcome this fragmentation.

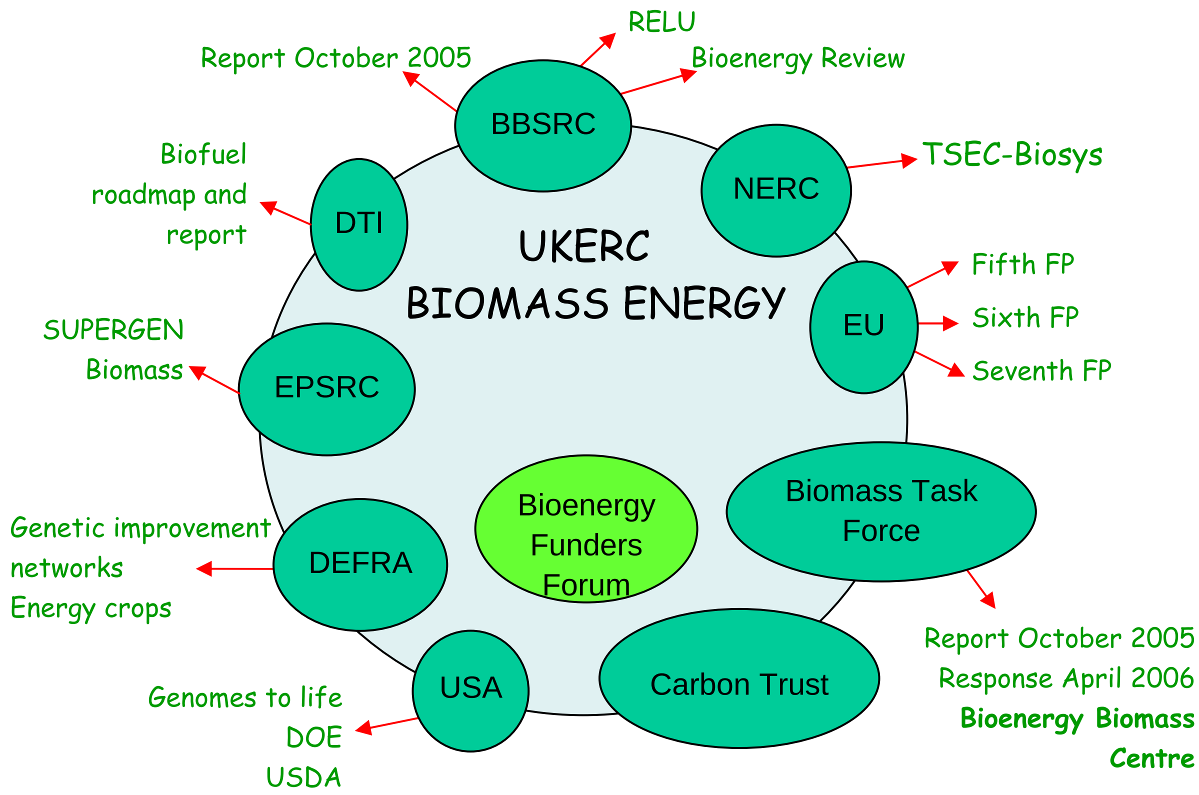


Figure 2: An overview of current activity in bioenergy science in the UK in 2005. The BBSRC review of bioenergy[7] is in consultation (May 2006), RELU research was initiated in 2006, as was TSEC-Biosys[10]. The seventh European Framework Programme is currently being drafted. The Biomass Task Force reported and central Government has responded to over 40 recommendations. The USA has finished a major roadmapping exercise in bioenergy with an emphasis on lignocellulosic biomass to bioethanol[5]. DEFRA have developed two GINS[8], one for miscanthus and one for SRC. The Carbon Trust has completed in 2005, an analysis of the bioenergy sector for the UK. EPSRC is coming to the end of the first SUPERGEN Bioenergy project[9] and DTI has undertaken some roadmapping activities, particularly for biofuels. The Bioenergy Funders Forum first reviewed UK research in bioenergy in 2000 and is currently working on an updated document.

Summary of major findings from the Research Atlas

- The UK bioenergy community has in the past lacked coherence and coordination, with several UK funding agencies and research programmes now initiated in bioenergy research. These are complemented by significant current activity in the USA and EU, particularly in research roadmapping and the development of action plans for bioenergy.

- The UK has strength in basic crop science, in particular for food crops. This includes breeding, improvement and agronomy as well as increased understanding of likely response to global change. However, this has not been applied widely to likely dedicated bioenergy cropping systems. On-going research within TSEC-Biosys and SUPERGEN-Biomass may address some of these gaps, but with limited long-term strategic vision.

- The land resource in the UK is finite. Predictions suggest that by 2020, Europe may be food-limited once more because of the impacts of climate change. Much remains unknown on how the agricultural landscape will develop in Europe. Of the 17 million ha of current agricultural land, 1 million ha is being suggested as a reasonable target for biomass heat and electricity (supplying 8 MT of biomass), representing the current amount of land dedicated to 'set-aside', but this land and that of arable may be required for food and for other bioenergy crops providing sugar and oil for liquid biofuels. Currently this predicted land competition remains unresolved.

- The BBSRC review[7] was undertaken with an expert group to consider the basic bioscience research that might is required to enable the bioenergy sector to develop in the UK.

- Co-firing of power stations with biomass[3] has to date largely relied on imports but new regulations demand more dedicated energy crops and this may stimulate increased growth of crops within a 25 mile radius of major coal burning power stations such as Drax.

- A complex regulatory framework is currently in place to support the development on new bioenergy projects. This includes the energy crop scheme, capital grants scheme and Renewables Obligation Certificates – more than 17 different schemes were identified by the Biomass Task Force and yet poor incentives for heat rather than power are apparent.

- The 'chicken and egg' concept is well recognised in the bioenergy sector, where feedstock or technology may be available but not integrated correctly, reflecting the complexity and number of potential bioenergy chains that rely on different feedstocks, and conversion technologies and which have spatio-temporal limitations. Each chain also has an environmental cost and these may differ considerably even when just comparing GHG emissions, hydrology and biodiversity.

Future Advances to 2050 and beyond

Combustion technologies for heat and electricity are largely 'mature' and so key challenges relate to the deployment and integration of these technologies for the future. In contrast, bioenergy crops and the supply of high quantity and quality feedstocks from a limited landscape remain largely unknown. New crop varieties, the introduction of GM technologies and the development of minimum input agricultural systems remain key research challenges, as does ensuring landscape-level changes that are environmentally acceptable with respect to biodiversity, water resources and GHG balance. By 2020 and beyond, gasification and other technologies may be deployed and advanced technologies for heat and power generation from green plants may be possible at commercial scale using biological rather than thermochemical conversion pathways. One advantage of such a change is that land requirements could be reduced although no figures are available to confirm this.

1. Key Challenges

a) *Land resource in the UK*

The limited land resource within the UK is a pressing issue in the development of dedicated bioenergy crops and also for the multi-purpose use of traditional food crops. For example, in future will wheat straw be fermented for ethanol or combusted for heat and electricity? Limited land resource is also partnered with the behaviour of growers which is driven by financial and regulatory incentives. Nevertheless all indications are that bioenergy could *potentially* contribute up to 7% of the UK demand for heat and electricity, but land will become an issue if it is deployed for liquid biofuels as this is in addition to this figure.

b) *Identification of a restricted number of bioenergy chains*

The complexity of a large number of potential bioenergy supply chains acts to prevent large-scale deployment of bioenergy for heat and power. A limited number of future bioenergy chains for 2010, 2020 and 2050 would enable clear planning and focus to be achieved.

c) *Development of better efficiencies within each bioenergy chain*

Although energy ratios for heat and electricity generation from biomass are much better than those for biomass to liquid fuels, there are still inefficiencies in the system, beginning with the capture of sunlight by the green plant and production of lignocelluloses from the process of photosynthesis. Further fundamental advances in plant biology are necessary in order for increases in efficiency to be achieved.

d) *Integration of policy mechanisms and a regulatory framework linked to long-term delivery of Emissions Trading Scheme*

Several Government departments and mechanisms exist to support this fragmented activity. Both a capital support programme and ROC for heat have been suggested as mechanisms that might provide a step-change incentive for development. Others will include more financial incentives for dedicated perennial bioenergy crops and the use of CHP in public buildings such as schools and hospitals. Central Government and RDA's must act together to ensure that these mechanisms are put in place. In the long term, the European Emissions trading scheme should help to give bioenergy a considerable boost, but until the cost of carbon is better understood, the future remains uncertain.

e) The uncertainty of climate change

The threat of a changing climate is ever-present. This is an over-arching future consideration, for example in determining strategy in crop improvement (Will we be growing the right crops in future? What will there yield be? Will we have more pests and disease?). Also in determining the balance between heat, electricity and liquid biofuels (Will the land resource be better used to grow wheat for ethanol or willow for heat?).

f) Biotechnology and the deployment of GM bioenergy crops

Public perception, understanding and acceptance of biotechnological routes to crop improvement may be a key challenge for the deployment of future bioenergy crops. On the one hand, technological advances may provide the step change necessary for improved yields, whilst, on the other hand, this may not be acceptable to the public. Urgent engagement with the public is required to understand this complex area further.

2. Key Scientific Advances

a) Designer crops for bioenergy

Using the latest biotechnological tools that are not necessarily 'GM', better crops for bioenergy should be developed. This requires step-change in current thinking that is only considering marker assisted selection of willow for pathogen resistance and improved yield. Systems Biology now enables us to follow gene, metabolite and protein profiles simultaneously and an array of genomic and post-genomic technologies linked to molecular genetics can be utilised to provide:

- High yield crops that require less inputs, thus improving efficiency further. A move to perennial (more efficient) and away from annual cropping systems. A 30% increase in yield will be necessary over the next 10 years for bioenergy crops and this should be tractable.
- Crops with different qualities: increased lignin for calorific combustion, or improved oils, starches and sugars for liquid biofuels.
- Crops with improved resistance to biotic and abiotic stresses that are likely to occur in future.
- Designer microbes and *in-situ* degradation of the plant cell wall, for combustion or other conversions

Model bioenergy crops include poplar (for which the DNA sequence and genomic resources are already available), maize and now *Brachypodium* as a model grass, which the DOE will sequence shortly. These are important resources for future advances. There are only limited germplasm collections for these crops and this should be addressed as a future priority.

Likely to occur: yes in the next 5-10 years

Future capacity: We have good core skills but these are not being currently applied to bioenergy.

Future applications: bioethanol, biodiesel, heat, power produced efficiently with better LCA.

b) New biological processes for bioenergy – microbial and in planta.

Many new advances are possible, including hydrogen from green plants through dark processes, artificial photosynthesis and other processes that are very much contained at the research (laboratory scale) at present.

Likely to occur for robust commercialisation: high risk-large reward.

Future capacity and applications: UK capacity is limited in this area, with the exception of one or two very strong groups.

c) *A land management framework linked to an ecological assessment tool*

Identify optimum land-use strategies for the UK biomass resource and likely future use of arable, set-aside and marginal land in a changing climate is required. We need to quantify the environmental consequences of bioenergy crops, developing tools for 'well to wheels' type analysis. Further research to capture the evidence base is required, including for bioenergy crops response to future climates, Some GHG data are missing and there are limited 'tools' for end-users. The EA has developed 'BEAT' to assess GHG emissions in planning new development in bioenergy but this area requires further input.

Likely to occur: yes

Future capacity and applications: UK has good expertise as yet not applied to bioenergy systems but that may be changing.

d) *Development of new gasification technologies and other advances linked to the biorefinery concept.*

New technologies for conversion are likely to develop to commercial scale by 2020. These will be essential again for improved efficiency but also because they offer the possibility of primary, secondary and tertiary uses of green plants as we move towards the bio-based economy.

Likely to occur: yes

Future capacity and applications: wide ranging potential to utilise low-input lignocellulosic crops for CHP and then link this to the extraction of other bioresources.

e) *Identification of a limited number of bioenergy chains*

It seems likely that focus on a limited number of bioenergy chains would be useful. Which should be chosen? USA roadmapping suggests all future activity will focus on improving the quality and quantity of biomass in green plants and also improving all biochemical steps in the bioethanol synthesis pathway.

Likely to occur: yes in both USA and Europe – better coordination required.

Capacity: Potential good, but no strategic thinking in the UK

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Abbreviations Used

GHG – Greenhouse gas
CHP – Combined heat and power
GM – genetic modification
DOE – Department of Energy, USA
DNA – deoxyribonucleic acid
RDA – Regional Development Authority
ROC – Renewables Obligation Certificate
DEFRA – UK Department for environment farming and the rural environment
RCEP – Royal Commission for Environmental Pollution
DTI – Department of trade and industry
TSEC-BIOSYS – Project to analyse UK bioenergy demand and supply, as part of 'Towards a Sustainable Energy Economy' programme
SUPERGEN – Bioenergy project within the 'Sustainable Energy' Programme of EPSRC (Engineering and Physical Research Council)
NERC – natural Environment Research Council
BBSRC – Biotechnological and Biological Research Council
GINs – Genetic Improvement Network
SRC – Short rotation coppice
RELU – Rural Economy and Landuse Programme
RCEP – Royal commission for Environmental Pollution
EA – Environment Agency

3. Annex 1: Summary of basic, strategic and applied research funding in bioenergy in the UK – 2006. Basic and applied strategic research

Table 1: Research Funding

Programme	Funding Agency	Description	Committed Funds	Period	Representative Annual Spend
NERC Towards A Sustainable Energy Economy	NERC / EPSRC	A whole-systems approach to analysing bioenergy demand and supply: mobilising the long-term potential of bioenergy. A multidisciplinary consortium to address gaps in the whole system.	£2.2M	2005-2009	£500,000
RELU - Rural Economy and Land Use, Research Councils UK	BBSRC / ESRC / NERC	Social, Economic and Environmental implications of increasing rural land use under energy crops. This project integrates social, economic, hydrological and biodiversity studies in an interdisciplinary approach to develop a scientific framework for Sustainability Appraisal (SA) of the medium and long term conversion of land to energy crops. We will provide scientific tools for updating Best Practice Guides and Environmental Impact Assessments, Strategic Environmental Assessments or SAs involving projects, policies or programmes where increased planting of energy crops is proposed or anticipated. The project profits from involvement of the Regional Development Agencies of the East Midlands and South-West regions used as study areas, industry representatives and DEFRA.	£859,000	2006-2008	£285,000

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Programme	Funding Agency	Description	Committed Funds	Period	Representative Annual Spend
Supergen	EPSRC	The SUPERGEN Biomass, Biofuels and Energy Crops Consortium, will carry out research into renewable energy generation from biomass - any plant material which can be used as a fuel, such as wood, agricultural waste and vegetable oils. Researchers will be studying the production of several types of biomass and investigating their behaviour in thermal conversion processes. The conversion processes will be studied for production of bio-fuels that can be used to generate renewable energy more efficiently. The results will be used to create computer models for designing and maximising the efficiency of the thermal processes, and to identify the ideal specifications of biomass fuels for different processes. System studies will evaluate the performance, cost, and socio-economic benefits of the full range of bio-energy systems considered.	£2.9M	2003-2007	£75,000
Supergen	EPSRC	The UK Sustainable Hydrogen Energy Consortium (SHEC) was established on 1 April 2003 by the EPSRC (in collaboration with the BBSRC, ESRC and NERC) as part of the SUPERGEN Initiative. SHEC will target many of the forefront fundamental, multidisciplinary research challenges in the production, storage, distribution and utilization of hydrogen. In addition, we will study the feasibility and acceptability of sustainable hydrogen as an energy carrier through a range of socio-economic projects, ranging from the public awareness and acceptability of hydrogen, impact analyses and regulatory issues.	£3.5 M	2003-2007	£900,000

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Programme	Funding Agency	Description	Committed Funds	Period	Representative Annual Spend
Energy crops – genetic improvement	DEFRA	Underpinning and strategic research to deliver improved grass and tree crops for bioenergy, with high yield and pest and disease resistance. Two networks have been initiated. The first, BEGIN, aims to produce improved willow genotypes with high yield and improved pest and disease resistance. The second is for the improvement of the grass Miscanthus.	£3.5 M	2003-2008	£90,000
UKERC	EPSRC / NERC / ESRC	Networking and development of the research atlas and roadmap for UK Bioenergy Research. Contribution to TSEC.	£290,000	2005-2009	£50,000
Responsive Mode	BBSRC	The Plants and Microbial committee of BBSRC research topic 'Fossil carbon substitution: biomass to biosynthesis	Limited to date	2005-	Limited to date
Responsive Mode	EPSRC	-	variable	2002-current	Variable
SUE Waste Consortium Programme	EPSRC	Cluster on waste, water and land management			

Table 2: Applied research (inc RDA support) Research Funding

Programme	Funding Agency	Description	Committed Funds	Period	Typical Annual Spend
New and Renewables Energy Programme	DTI	Past research on fuel supply systems for energy crops, and agricultural and forestry residues, including - Target of doubling energy crop yields (based on SRC willow) from current yields of 8 oven dry tonnes (ODT) per hectare. - Equipment development for reduced costs and increased efficiency. Energy crop production work supported by DTI is coming to a conclusion. Future projects to be funded on a responsive basis through the Technology Programme, and taking account of the Innovations Review, but energy crops are unlikely to be a priority. The New and Renewable Energy R&D Programme is now being delivered through the Collaborative R&D Business Support Product. Open competitions for funding under this product happen twice a year.			

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Programme	Funding Agency	Description	Committed Funds	Period	Typical Annual Spend
Technology Programme	DTI	A new DTI Technology Innovation Programme was announced in April 2006. Technology priority areas include emerging Energy Technologies (**Low Carbon Energy Technologies, including development of the biorefinery concept**); Sustainable Production & Consumption (Energy Efficiency Technologies); Bioscience & Healthcare (Exploitation of Plant and Microbial Bioscience for Industry, Safety Biomarkers for Pharmaceutical Development); Advanced Materials (Materials for Extended First Use and Re-use); Information & Communication Technology (Data, Scientific and Medical Visualisation for innovative products and services).	£80 M in total	2006-	Approximately £20 M
Applied Research Grants	The Carbon Trust	The Carbon Trust is an independent company funded by Government. Their role is to help the UK move to a low carbon economy by helping business and the public sector reduce carbon emissions now and capture the commercial opportunities of low carbon technologies. It supports the development of low carbon technologies through R&D grants, with several of these placed within the Bioenergy sector in recent years. Other activities of the trust with specific relevance to Bioenergy are given below.	£672,000	2003-2007	
Carbon Vision	The Carbon Trust	The overall aim of this Carbon Trust project is to develop a pragmatic life cycle methodology that will allow a systematic estimation of carbon inventories in different industrial sectors that supports the incorporation of the carbon intensity of the full supply chain. This will involve both environmental and economic aspects of carbon footprints and embodied carbon, enabling estimation of "carbon added" and "valued added" at each stage in the supply chain.	£1.05M	2005-2008	

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Programme	Funding Agency	Description	Committed Funds	Period	Typical Annual Spend
Biomass Heat Accelerator	The Carbon Trust	The broad aim of BHAP is to help make the UK biomass heat market self-sustaining by reducing costs and addressing supply chain risks. The project aims to work with existing and new sites to develop benchmarks from robust case studies, identify and demonstrate cost reductions, and raise awareness amongst end users and other stakeholders.	£5.0 M	2006-2011	
Tyndall Centre	NERC / EPSRC / ESRC	Trans-disciplinary research related to climate change, with some limited desk-studies on low carbon economy related to bioenergy.	£200,000	2001-2006	
SEERAD	Scottish Executive	Currently reviewing priorities in the area, and reviewing ways forward for biofuel development in Scotland. SEERAD has indirect investments through 'GREEN grain', co-funded with Defra and HGCA (genetic reduction of nitrogen emissions and growing costs of wheat production whilst enhancing the value of wheat grain for the bioethanol industry amongst others).			

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Programme	Funding Agency	Description	Committed Funds	Period	Typical Annual Spend
Environment Agency	Environment Agency	Funds small-scale hydroelectric and biomass energy. Developing BEAT: computer-based predictive tool for potential environmental impacts and mitigation responses to aid decision-making on biomass developments from an environmental perspective, especially for environmental impact assessment (EIA) scoping.			
Forest Research	Forestry Commission	Co-funding, with DTI/Defra/DARD, the project 'Yield Models for Energy Coppice Poplar and Willow- Phase IV.' Other activity is highly applied, near market, e.g.: - Extraction, drying and chipping of woodfuel from plantations-ash recycling - Medium to large-scale recovery, baling, handling of residue from logging.	£2M approx	1999-2006	
Biomass Energy Centre	DEFRA	Established in May 2006, the 'Biomass Energy Centre' is an expert centre for advice to growers, technologists and developers in bioenergy.	£20,000	2006	

4. Biofuels and the biorefinery concept

A short review prepared June 2006 for the OSI Foresight scanning project in Renewable Energy

Background

Liquid biofuels may be made from a variety of biomass sources using a number of conversion routes to produce several types of product suitable for road and other forms of transportation fuel. Fuels include bioethanol, biodiesel and other bio-based products such as biobutanol. Feedstocks include oil-based crops such as oil seed rape, which are used for the production of biodiesel, and sugar- and starch-based crops such as sugar beet, which are used for the production of bioethanol. All lignocellulosic biomass (all biomass, i.e. mostly plant cell walls, which have a high carbon content) can be converted to liquid fuels through biological processes (esterification, fermentation) or through thermochemical routes such as pyrolysis. Hydrogen may also be produced from biomass. As with heat and electricity, this complexity may hinder the development of biofuel chains, but this may be advantageous to the UK, where identifying a clear 'winner' is unlikely, given the complexity, but also the small size, of our agricultural landscape. As part of a wide range of measures drawn up by the EC in response to international agreements to reduce greenhouse gas emissions, the European Commission has introduced the Biofuels Directive, which the UK has committed itself to. This means that the UK is moving towards the development of transport biofuels with a target of 5.75% replacement by volume of petroleum-based fuels by 2010[18]. It has been estimated that liquid fuel demand in the UK in 2010 will be 44.5 million tonnes, requiring 2.56 million tonnes of biofuel at that time, providing a carbon saving of approximately 2 million tonnes. In the international market, biodiesel (derived commercially from vegetable or other plant oils) and bioethanol (derived from fermentation of starch or sugar crops) dominate as the most technically feasible and commercialized alternative renewable fuel sources. Biodiesel can also be derived from animal fats, grease and tallow, which would otherwise be disposed of as waste.

Table 3: Summary of commercial activity in biofuel production in the UK, May 2006

Name	Description	Subtopic	Funding	Duration
British Sugar	55,000 tonnes per annum (70 million litres) plant being constructed in Wissington, Norfolk	Bioethanol production at commercial scale	£20 million capital cost of plant	Construction initiated in January 2006
Greenergy	Biodiesel plant at Immingham on the east coast of England. The plant will initially process 100,000 tonnes/114 million litres of biodiesel per year and is expected to begin by the end of 2006. Preliminary planning and design work for a second phase to double our biodiesel production capacity at Immingham to 200,000 tonnes/228 million litres per year	Biodiesel production at commercial scale	Unknown	Construction to be completed by end of 2006
Green Spirit Fuels	Wessex Grain Company to develop wheat grain as a source of bioethanol in the UK. Plant in development in Somerset for 141 million litres bioethanol (100,000 tonnes) by 2007	Bioethanol production	£50 million	Construction to be completed in 2007

The UK has seen considerable industry 'pull' in the area of biofuels in the last year or so following the introductive of the Directive. A summary of some of this activity at May 2006 is shown in Table 3. It is also apparent that the current high price of oil and likelihood of a sustained high price is having a marked effect on the development of a biofuel industry. Bauen[1] showed that biofuels begin to become financially competitive over $65 per barrel of oil and additional environmental benefits are not even considered in such an analysis. For sugar-beet bioethanol development, it is also likely following EU deregulation of sugar prices which in the past has effectively inflated sugar prices by three times of those on the world market. A summary of UK biomass resource suitable for liquid bioenergy production is given in Table 4. It reveals that it is unlikely that any single supply stream will be able to meet the UK commitment to biofuels for 2010.

Table 4: Summary of likely potential feedstock availability in the UK, processing routes – meeting the 2010 Biofuel Directive

NB. It should be noted that this is a broad-brush picture painted for the purpose of this short review and a further complete analysis of UK potential feedstock supply should be encouraged, considering new perennial crop systems and second-generation biofuels. A review by the National Farmers' Union[14] provides broadly similar figures.

Crop type	Harvest fraction	Feedstock area (100 ha)	Percentage of current crop area	Fuel proposed (million tonnes)	Biofuel
Oil seed rape	Seed oil	459	+102 %	0.7	Crushing and esterification of the oil to biodiesel
Wheat	Straw				Breakdown, hydrolysis and fermentation of lignocellulose to bioethanol
Wheat	Grain	346	21 %	0.8	Breakdown, hydrolysis and fermentation of starch to bioethanol
Sugar beet	Sugar	202	+202 %	0.83	Breakdown, hydrolysis and fermentation of sugar to bioethanol. A recent suggestion is the formation of biobutanol from this route
Waste oil/fat	–	-	-	0.1	Biodiesel

Current agricultural practices in the UK suggest that the main sources of liquid biofuels in the near future will be bioethanol, derived from wheat grain and sugar beet, combined with biodiesel from oil seed rape and also oil waste products. For dedicated cropping systems, analysis reveals that approximately 1 million ha of agricultural land would be required to meet the 2010 biofuel target (separate to those requirements highlighted for biomass for heat and power) for the UK, and that this would require more than doubling the agricultural land dedicated to oil seed rape production, and doubling the recovery of wheat for bioethanol. In Table 4, the equivalent of 0.8 million tonnes of fuel produced from wheat grain is currently exported from the UK in most years, and so it would be useful to link this to bioethanol production, as proposed in new developments, rather than export. Any more than doubling of oil seed rape production is unlikely to be feasible since this might require the use of 'set aside' land, with implications for a loss of biodiversity and further intensification. This implies that the UK can, in theory, make the Directive commitment by 2010 if commercialisation is successful, as seems likely. In general, it should be acknowledged that the use of annual crops for liquid biofuels provides a poor energy balance and efficiency compared to the use of perennial crops, with their lower inputs and higher biomass yields per hectare. The use of annual versus perennial should be considered in much greater detail in future, following recent US analysis, with annual crops seen only as a 'short-term fix'[5].

Current status of research

In general, research dedicated to biofuels in the UK is fragmented and extremely limited, but core expertise to address some of the issues highlighted below is extremely good.

Fundamental plant biology and crop science

It is clear from the analysis above, that any technology available to increase crop yield in current and future climates should be of value to the future development of the biofuel industry. More importantly, improving plant quality, for example, by increasing sugar content or starch content and decreasing protein content, will enable efficient process and extraction for biofuel.

- The UK has good expertise in crop science and plant improvement, but it is only being applied in a limited way to bioenergy cropping systems.
- The UK has excellence in fundamental plant science research, but it is only being applied in a small way to address specific bioenergy quality and quantity traits (e.g. different oil quality for better processing in oil seed rape).
- GM technologies and non-GM biotechnology may provide the step-change necessary for future improvements, but the public acceptance of these technologies is still uncertain.

Industrial microbiology

New enzymes, plant-based enzymes, new microbes and better fermentation are examples of how the processes for biofuel production could be improved. We have good expertise in microbiology, but this is not being largely applied to the production of biofuels.

Environmental impacts

In the UK and Europe, one of the key drivers for investment in biofuels is environmental – meeting our commitment to Kyoto and more generally wishing to develop carbon-neutral technologies is of high strategic importance. Therefore considerable emphasis is needed to assess the whole-lifecycle carbon costs of all of the technologies considered above. Currently, there is some discrepancy and contention between different studies to assess the greenhouse gas balance of a variety of bioenergy cropping systems. At the point to crop harvest, the greenhouse gas or carbon costs are very dependent on what the bioenergy crop might be replacing. There are large carbon savings, for example, if winter wheat is replaced with oil seed rape, but these savings are more than trebled if trees or grasses (perennial crops) are grown instead (Pete Smith, Aberdeen University, personal communication). If conversion and production are considered, again lifecycle analysis may give contrasting results. Current research tools are now available to ensure correct full lifecycle analysis and these must be linked to policy developments to ensure that environmental as well as economic drivers are considered in any regulatory framework.

Conversion technologies

Engineering technologies for bioethanol and biodiesel are more or less available 'off the shelf'. However, inefficient and expensive pre-treatments, enzymes and chemicals are involved in these processes that form the challenge for future research.

5. The Future challenge for 2050 and beyond

Future developments and the necessity for step-change research discovery: making the biorefinery work

Although technically possible to meet the 2010 Biofuel Directive target from domestic feedstock resources, it is unlikely that this target can be achieved with current cropping systems. This is because of farm-scale considerations, where crop rotations determine farm-scale plans, and also because of spatial limitation, in growing sugar beet, for example. It also assumes an extra 1 million hectares of agricultural land will be available for this activity, while this amount of land is also being considered to grow dedicated biomass bioenergy crops for heat and power. This scenario also assumes that no further demand for biofuels will occur and yet all energy analyses suggest that this is unlikely. Although imports of bioethanol and biodiesel will contribute to our net requirement, in the long term, with full lifecycle analysis, this may not be environmentally sustainable, although this needs to be clearly quantified and regulated.

In contrast, the UK has a considerable lignocellulosic biomass resource. Lignocellulose is the intimate mix of plant biomass that constitutes the cell wall – a complex material largely consisting of lignin and cellulose. Several million tonnes of forest residues (waste wood) may be available in the UK each year, for example, and of this, only approximately 1 million tonnes is currently recovered and utilised. Other lignocellulosic resources – for example, 0.2 million tonnes per annum of wheat straw, forest arboricultural waste of 1–2 million tonnes – are also available. Dedicated lignocellulosic biomass crops include woody short-rotation coppice (SRC) willow and poplar, and miscanthus grass. These crops, unlike conventional annual crops such as oil seed rape, are low-intensity, low-input crops with a much improved greenhouse gas balance along with other environmental benefits such as enhanced biodiversity. All research analysis suggests that perennial crops will be favoured over annual crops since they have a greater seasonal capture of solar energy and, again, produce biomass without the complications or reproductive yield.

Linked to this and given limitation on land resource and the concept of enhanced efficiency, in the future plants may be used more generally as part of the bio-based economy, as we become less dependent on the oil-based economy. Plants are the ultimate source of renewable sustainable bioproducts and this extends way beyond simply using plants for energy. High-quality, low-volume chemicals will be harvested alongside that of energy. Several such conversion routes are possible, but the basic feedstock for all second-generation biofuels will be lignocellulosic[8.] Step-wise research challenges linked to this development are necessary, and currently it is extremely difficult to extract and process lignocellulosic feedstocks efficiently. Several bottlenecks exist and some are identified below[2, 5, 8].

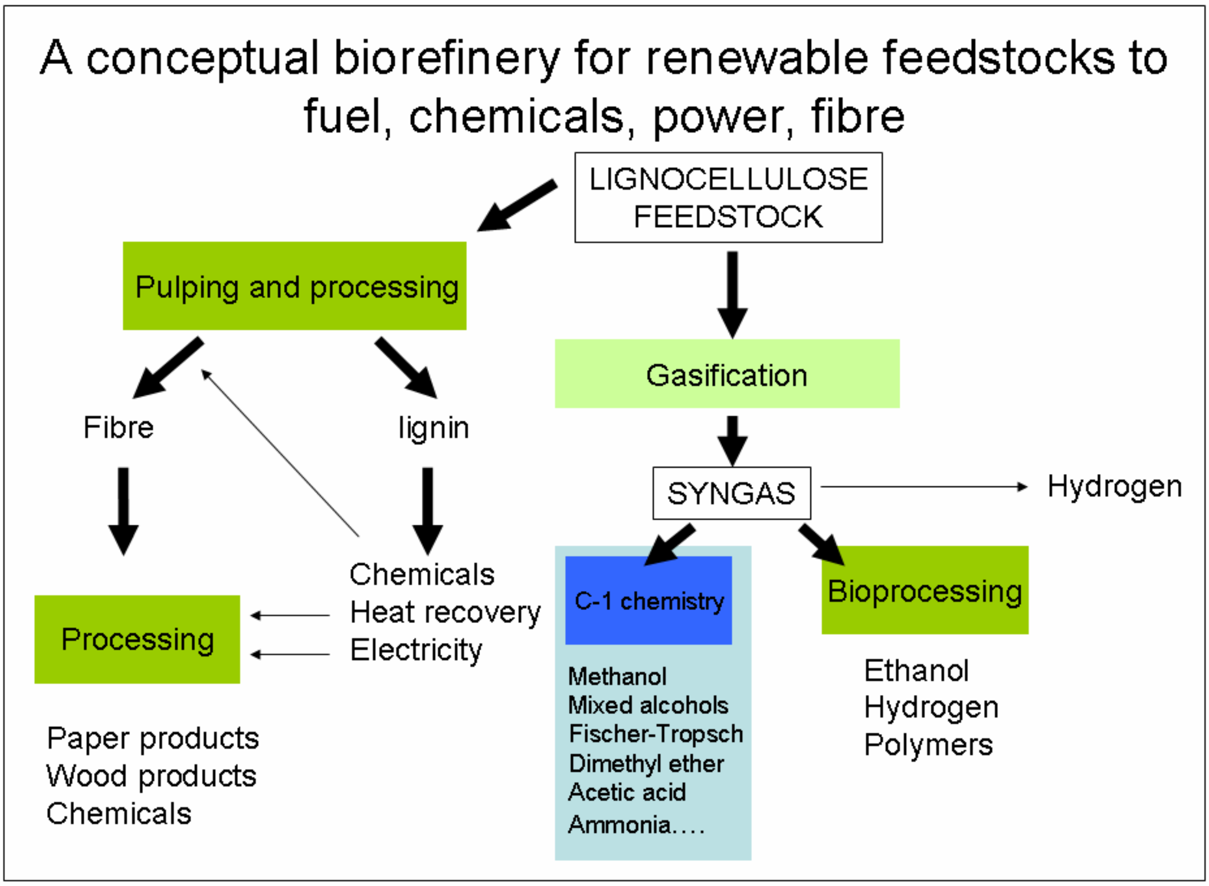

Figure 3: A conceptual biorefinery with lignocellulose feedstock being used for lignin to energy to combustion through thermochemical process, pulp recovery for paper, gasification for gaseous fuel and biological processing for bioethanol. Other fuels are also possible.

Key scientific advances necessary for the biorefinery to work

Challenge: better use of available feedstock

Plants cell walls are lignin and cellulose. These complex structures are still far from being understood and key to their utilisation for bioenergy will be new research on understanding construction and deconstruction. Linked to this, a key scientific challenge is to make hydrolysis and fermentation reactions effective.

Likely to occur? Up to five years – tractable and could occur over a five-year timescale

Challenge: new designer feedstock and microbial processes for breakdown

Fundamental biosciences must be utilised to develop new and novel plants with different plant characteristics. For example, a new generation of bioenergy plants with enhanced sustainability, yield and altered composition; high-lignin plants for pyrolysis and gasification; high-cellulose plants for bioethanol; plants that breakdown easily. This requires a systems biology approach linking biology to phenotyping to high-throughput computing. New microorganisms and biological routes to plant breakdown are required. Novel discoveries to improve hydrogen production from plants may also be possible.

Likely to occur? 5–10 years – heavy investment by the US, and BP has just announced the creation of its new Bioenergy Centre to be funded either in the UK or the USA.

Challenge: better technologies for assessment of lignocellulose and breakdown processes
A cross-cutting interdisciplinary approach and new technologies are required to visualise plant cell walls, microbial systems and their functioning. New computing developments will be necessary to enable the biorefinery concept at all levels, from modelling microbial function to predictive experiments through to systems engineering and moving to pilot-scale and commercial plant.
Likely to occur? More speculative, but possible 10+ years.

Challenge: Imported versus home-grown and sustainable liquid biofuels
Land resource in both the UK and EU will limited our net contribution to biofuel supplies. Estimates vary but all suggest that we cannot be self sustaining in liquid biofuels without a major impact on agricultural land and food supplies. Import of liquid fuel may involve destruction of native forests or other environments with a loss of ecosystem services. A major challenge will be to ensure a sustainability framework for the global deployment and exploitation of biofuels as a commodity.
Likely to occur? International environmental protocols and agreements do exist, but are often ineffective e.g. Kyoto, although some exceptions exist e.g. Montreal Protocol. This will require a major international research and policy effort.

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Appendix

Analysis of the evidence base for comparison of greenhouse gas emission and energy balance of several contrasting bioenergy conversion routes (from Rowe et al., in press).

Table A1: Greenhouse gas emission and energy ratio of biomass production of utilisation

Fuel source	**GHG emissions** g C eq. MJ^{-1} of biomass	**Energy ratio** $MJ_{produced}/MJ_{input}$	**Author**
SRC willow	0.19[a]	11[a]	Heller et al. (2003)
SRC Willow	1.7–2.7[a]	17–20[a]	Dubuisson and Sintzoff (1998)
SRC willow and poplar	1.3[a]	28.57[a]	Matthews (2001)
SRC willow	-	21[a]	Börjesson (1996)
Reed canary grass	-	11[a]	
SRC willow	1.36[a]	-	Lundborg (1997)
Miscanthus	0.512[a]	35.86[a]	Bullard and Metcalfe (2001)
Switchgrass	0.629[a]	28.97[a]	
Reed canary grass	0.89[a]	20.4[a]	
SRC willow	0.13[b]	13[b]; 55[c]	Keoleian and Volk (2005)
Combined heat and power (small-scale) from gasification of SRC willow	1.23[d]	10.34[d]	Adapted from Elsayed et al. (2003)
Electricity from gasification of SRC willow	2.04[d]	6.21[d]	
Electricity from pyrolysis of SRC willow	4.13[d]	3.11[d]	
Electricity from combustion of SRC willow	6.54[d]	2.73[d]	
Electricity (large-scale) from miscanthus	7.09[d]	3.68[d]	

(a) Values for harvested crops (chipped or baled)
(b) Values for production and gasification of willow for power generation
(c) Values for willow at farm gate
(d) Values for production and utilisation for power generation

Table A2: Greenhouse gas emission in carbon equivalents and energy ratios of the production of bioethanol and biodiesel

Fuel type / source / energy source used for production	**GHG emissions** g C eq.MJ^{-1} of biomass	**Energy ratio** $MJ_{produced}/MJ_{input}$	**Author**
Sugar beet	-	12[a]	Powlson et al. (2005)
Wheat	-	7.2[a]	
Oil seed rape	-	4.49[a]	
Bioethanol/maize	2.64 to 9.38	1.2 to 1.9	Seungdo and Dale (2005)
Ethanol/grain/fossil fuel	23.18	-	Lundborg (1997)
Ethanol/forest residues/waste heat	1.64	-	
Biodiesel/oil seed rape	4.09	-	
Biodiesel/oil seed rape	11.18	2.29	Elsayed et al. (2003)
Ethanol/wheat straw	3.54	–35.71 (4.1)[a]	
Ethanol/sugar beet	10.91	2.02	
Ethanol/wheat	7.91	2.16	
Bioethanol/wheat/natural gas and grid electricity	11.99	1.55	Mortimer et al. (2004)
Bioethanol/wheat/natural gas combined heat and power, with steam turbine	11.99	1.67	
Bioethanol/wheat/natural gas combined heat and power, with gas turbine	8.99	2.47	
Bioethanol/wheat/straw fired combined heat and power, with steam turbine	3.82	–14.28 (2.41)[b]	
Bioethanol/sugar beet/natural gas and grid electricity	12.81	1.21	
Bioethanol/sugar beet/natural gas combined heat and power, with steam turbine	10.63	1.47	
Bioethanol/sugar beet/natural gas combined heat and power, with gas turbine	5.99	2.78	
Bioethanol/sugar beet/straw-fired combined heat and power, with steam turbine	–29.72 (8.45)[b]	–1.92 (2.64)[c]	

(a) Excluding credit for electricity and acetic acid production from by-products
(b) Excluding credit for electricity exported to grid
(c) Excluding credit for exported electricity and lime